NANJING UNIVERSITY

Exclusive Vector-Meson Photoproduction as a Probe of Hadron Structure

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Theoretical Motivations and Empirical Evidence for Diquark Correlations in Hadrons,
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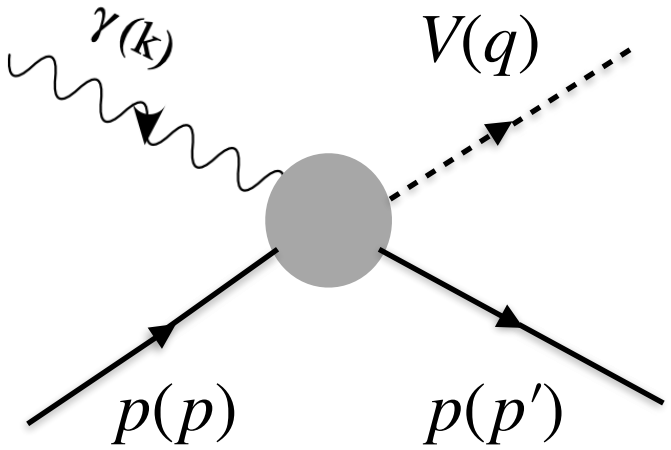
Exclusive Vector-Meson Photoproduction process

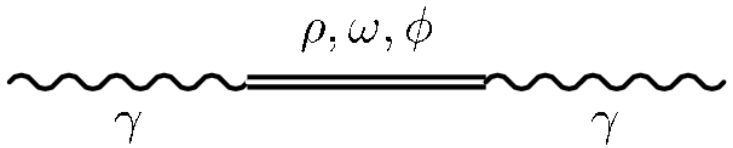
➢ $\gamma + p \to V + p$ with $V = \rho, \phi, \omega, J/\psi, \Upsilon$



➢ Historical development:

✓ 1960s–70s: Does the photon have a hadronic component?

Test Vector meson dominance (VMD) and photon–vector-meson connection

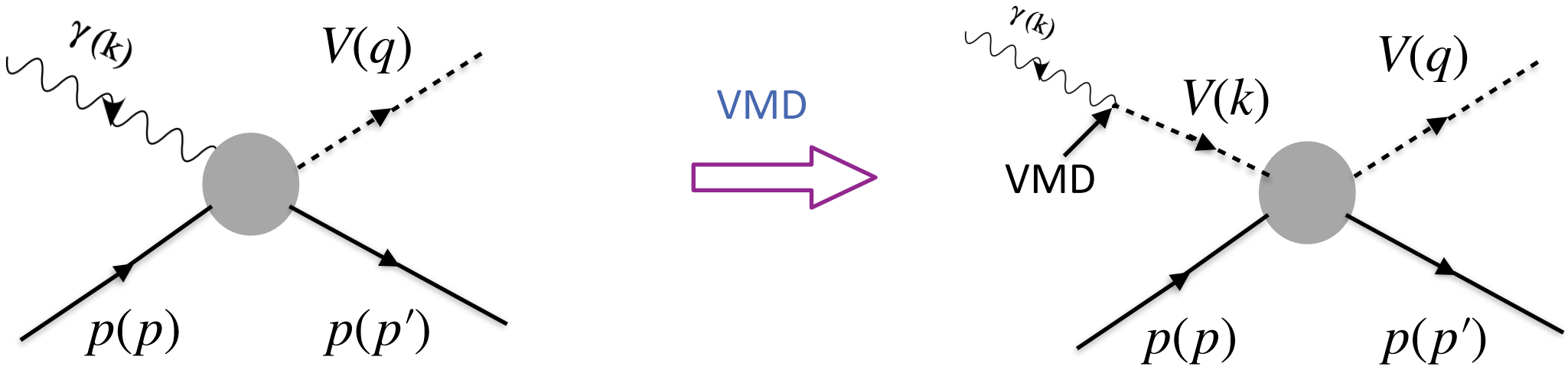


$$J^{\gamma}_{\mu} = \sum_{V} \frac{m_V^2}{f_V} V_{\mu}$$

J. J. Sakurai, Theory of strong interactions, Annals Phys. 11 (1960) 1–48.

✓ photon current is practically indistinguishable from vector meson current

Vector Meson Dominance (VMD)



$$\gamma + p \to V + p$$

$$\gamma + p \xrightarrow{\gamma \to V} V + p \to V + p$$

➢ Two steps:

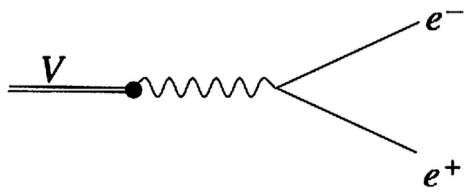


✓ $\gamma(Q^2 = 0) \to V(Q^2 = -m_V^2)$

✓ $V(Q^2 = -m_V^2)\, p \to V(Q^2 = -m_V^2)\, p$

Vector Meson Dominance (VMD)

- In the VMD-based Pom-Donnachie and Landshoff (DL) model, VMD coupling constant is determined by the $J/\psi \to \gamma \to e^+e^-$ decay with at $Q^2 = -m_V^2$.
- The photoproduction $\gamma + p \to V + p$ occurs at $Q^2 = 0$.



- The use of VMD is questionable.

- Thus, the phenomenological procedure would introduce an off-shell factor
  - ✓ Naive VMD effectively assumes $g_{\gamma V}(Q^2)\Big|_{Q^2=0} \approx g_{\gamma V}(Q^2)\Big|_{Q^2=-m_V^2}$.
  - ✓ Introduce a off-shell factor $g_{\gamma V}(0) = F_{\text{off}}(0)\, g_{\gamma V}(-m_V^2)$ with $F_{\text{off}}(0) = 0.4 - 0.7$.
  - ✓ An effective $\gamma - V$ transition from, but is not derived from QCD.
  - ✓ Instead of introducing an unknown $F_{\text{off}}(0)$, one can calculate the photon-quark vertex and the $q\bar{q} \to J/\psi$ transition explicitly.

Vector Meson Dominance (VMD)

- Photon in photoproduction is real, $Q^2 = 0$, on-shell vector meson satisfies, $Q^2 = -m_V^2$, those are not the same kinematic point.

- Dressed photon-quark vertex has vector-meson poles

$$\Gamma_\mu^\gamma(k;Q) = \Gamma_\mu^{\mathrm{reg}}(k;Q) + \sum_V \frac{f_V m_V}{Q^2 + m_V^2} \Gamma_\mu^V(k;Q) + \cdots .$$

  - ✓ Near the pole, $Q^2 = -m_V^2$, the pole term dominates, so that

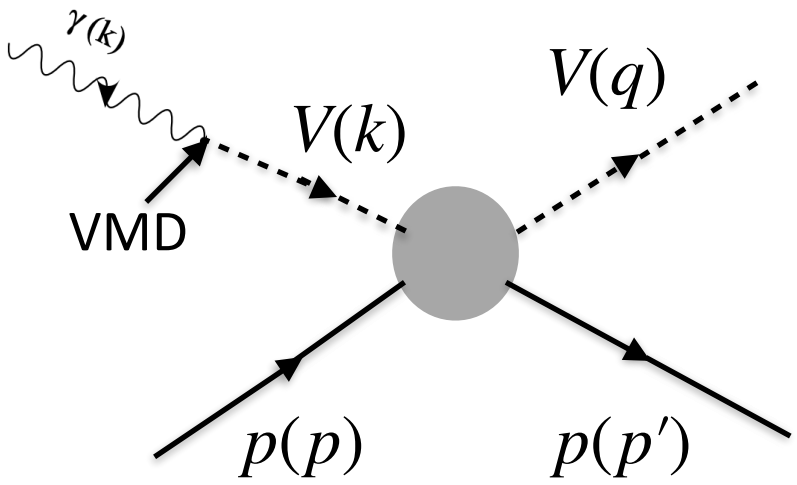
$$\Gamma_\mu^\gamma(k;Q) \sim \frac{f_V m_V}{Q^2 + m_V^2} \Gamma_\mu^V(k;Q) .$$

  - ✓ But photoproduction is at $Q^2 = 0$, and there is no theorem saying that the pole term still dominates there.

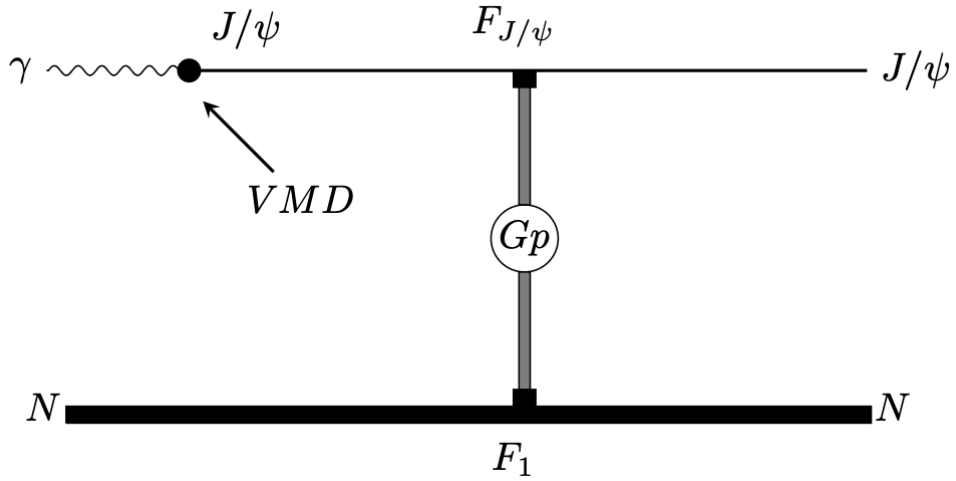
Pomeron exchange

✓ 1960s–80s: What causes high-energy diffraction?

Study Regge theory and Pomeron exchange



Pomeron exchange



Pomeron exchange

- ✓ The reaction is $\gamma + p \to V + p$, so after the interaction, the proton has not changed charge, baryon number, isospin, etc. γ and V has the same quantum number, therefore the exchanged object must carry vacuum-like quantum numbers.
- ✓ In particular, in QCD language it must be overall color singlet.
- ✓ Historically, before QCD, Regge theory introduced precisely such an exchange:

$$\mathbb{P} \equiv \text{Pomeron}$$

A. Donnachie, H. G. Dosch, P. V. Landshoff, and O. Nachtmann, Pomeron Physics and QCD, Cambridge University Press (2002).

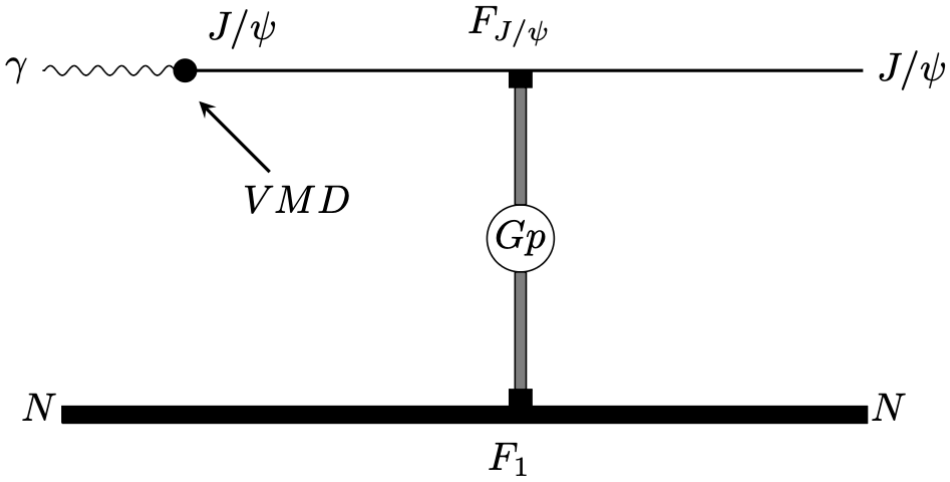
- ✓ 1980s–90s: What is the Pomeron in QCD?

  Connect Pomeron to color-singlet gluonic exchange
- ✓ Pomeron-photon analogy that Pomerons interact with quarks like photons. $\Gamma^{\mu}_{\gamma} = ie_q\gamma^{\mu}$, and $\Gamma^{\mu}_{\mathbb{P}} \propto \beta_0\gamma^{\mu}$. But it is charge-conjugation even and couples equally to up and down quarks.

Pomeron-exchange model of Donnachie and Landshoff (P-DL or P-am)

✓ $F_1(t)$: electromagnetic form factors of hadrons

$$F_1(t) = \frac{4m_N^2 - 2.8t}{(4m_N^2 - t)(1 - t/0.71)^2}$$



✓ $F_V(t)$: form factor for V

$$F_V(t) = \frac{1}{m_V^2 - t}\left(\frac{2\mu_0^2}{2\mu_0^2 + m_V^2 - t}\right)$$

✓ $G_P(t, s)$: the Pomeron propagator of the Regge phenomenology:

$$G_{\mathbb{P}} = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t) - 1\right]\right\}$$

T.-S. H. Lee, S. Sakinah, and Y. Oh, Models of J/ψ photo-production reactions on the nucleon, Eur. Phys. J. A 58 (2022) 252.

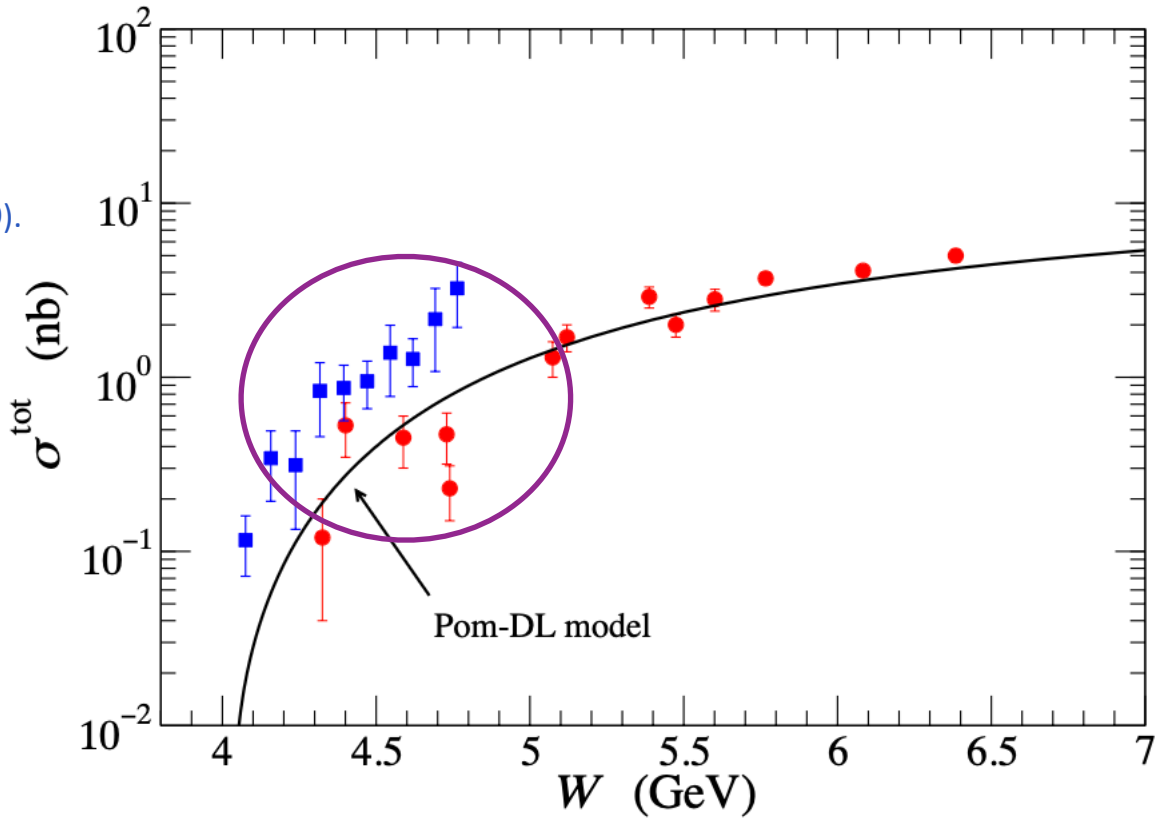
Pomeron-exchange model of Donnachie and Landshoff (P-DL or P-am)

- ✓ $\gamma + p \rightarrow J/\psi + p$
- ✓ Solid (blue) squares are the JLab data:

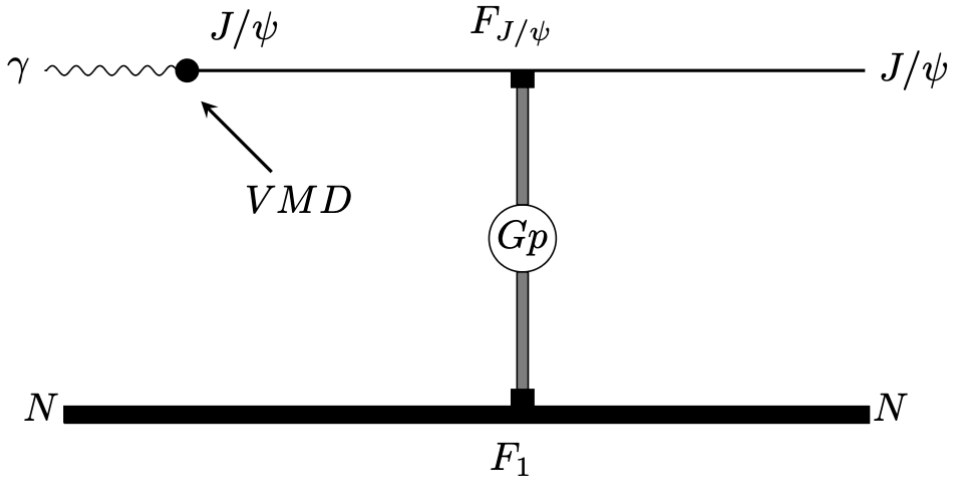
  Ali et al., GlueX Collaboration, First measurement of near-threshold J/ψ exclusive photoproduction off the proton, Phys. Rev. Lett. 123, 072001 (2019).

- ✓ Total cross sections using P-DL (solid line) are shown to be much smaller than the JLab data.

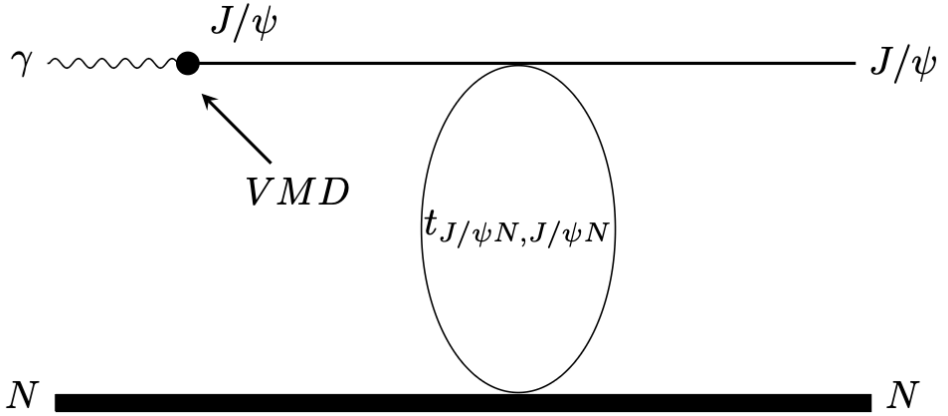
- ✓ The results is not unexpected since the use of Pomeron-photon analogy only accounts for parts of gluon-exchange mechanisms which may not be the dominant mechanism in the near threshold region.



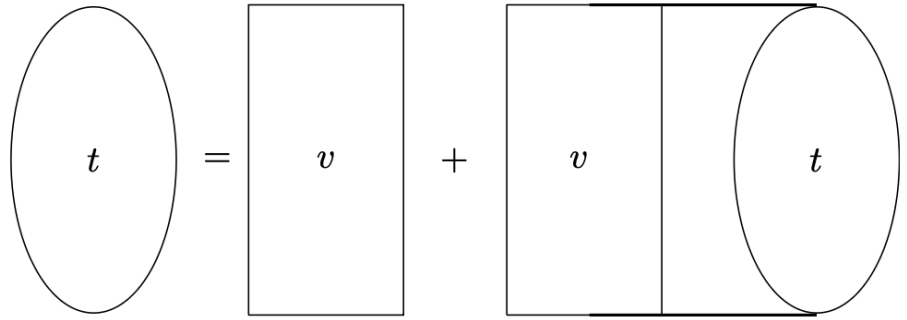
P-DL include J/Ψ-N potentials (Pom-pot)



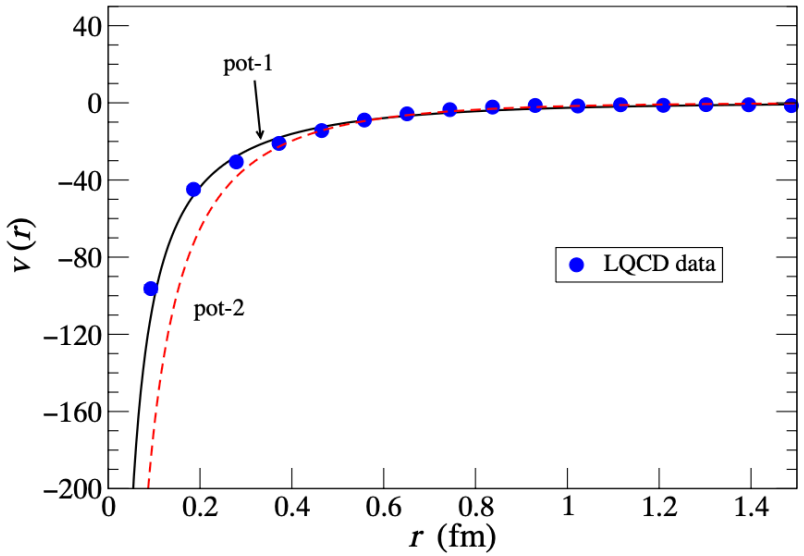
include J/Ψ -N potentials

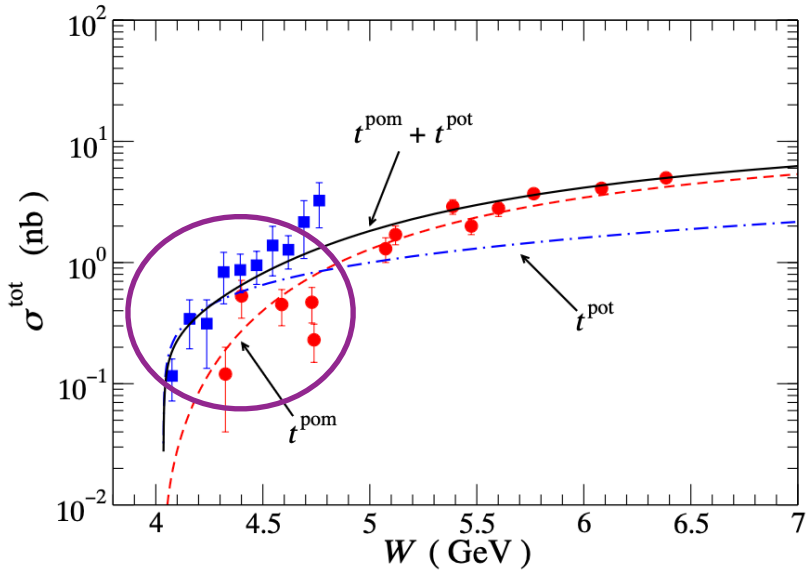


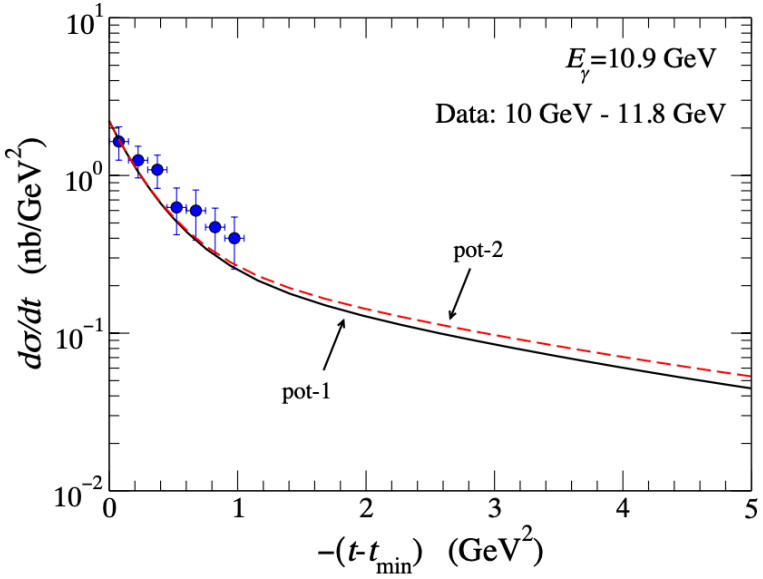
- ✓ $\mathbb{P} + J/\psi\, p$ rescattering
- ✓ Add a J/Ψ -N scattering amplitude generated from a J/Ψ -N potential which can be interpreted as the multi-gluon exchange mechanisms
- ✓ J/Ψ -N scattering amplitude is defined by the Lippmann-Schwinger equation.



P-DL include J/Ψ-N potentials (Pom-pot)







✓ J/Ψ -N potential

✓ total cross section

✓ differential cross section

✓ The Pom-pot model ($\mathbb{P} + J/\psi\, p$ rescattering) is a model which fits the data from threshold to very high energy W=300 GeV.

Near- threshold models: GPD-based model

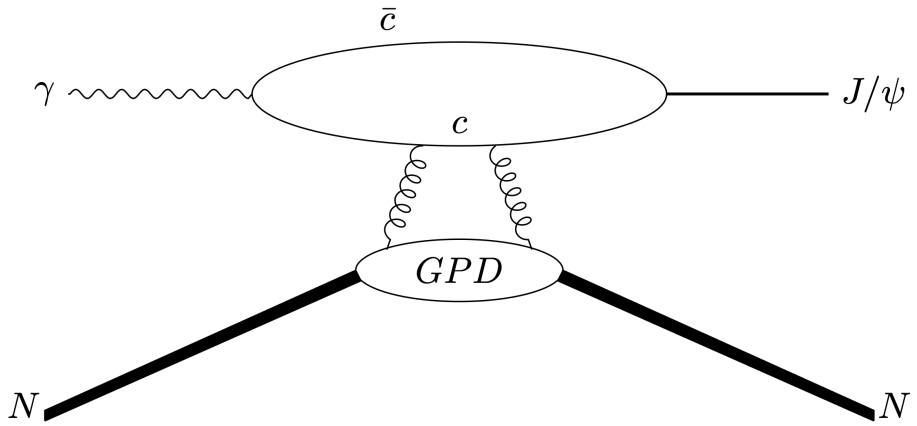
- ✓ 1990s–today: Can heavy quarkonium probe proton gluons?

  $J/\psi, \Upsilon$ provide hard scales

- ✓ JLab era: What happens near threshold?

  Proton glue, GPD/GFF proposals, trace anomaly, pentaquarks

- ✓ The J/ψ is approximately $J/\psi \sim c\bar{c}$, The proton valence structure is $p \sim uud$, so there is no common valence flavor between them.
- ✓ Because the process is exclusive, $p \to p$, the proton must remain a color singlet.
- ✓ A single exchanged gluon is color octet: 8, so it cannot by itself leave both external hadrons color singlets.
- ✓ The lowest perturbative color-singlet gluonic exchange is two gluons: $8 \otimes 8 \supset 1$.



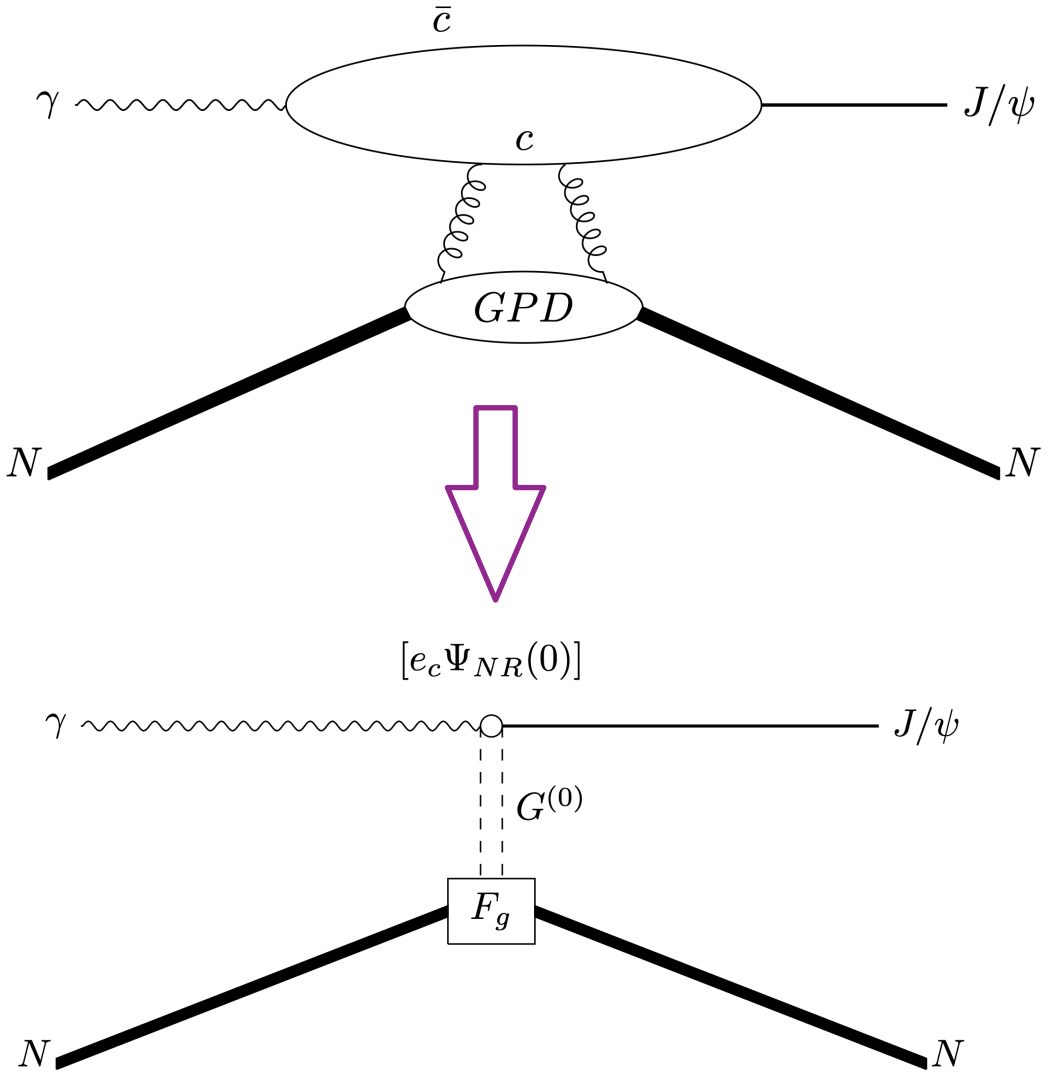
Near- threshold models: GPD-based model

- ✓ The two-gluon proton matrix element is schematically $\langle P' | A^{\mu} A^{\nu} | P \rangle$.
- ✓ Approximations: (1) use the threshold kinematics that the final J/Ψ and nucleon are at rest. (2) use a non-relativistic approximation for $\bar{c}c$ wavefunction of J/Ψ. (3) take the light front gauge $A^{+} = 0$.
- ✓ After the heavy-quark and nonrelativistic approximations, using threshold moment expansion, the amplitude is related to the gluon GPD $F_g(x, \xi, t)$.
- ✓ The relevant quantity as

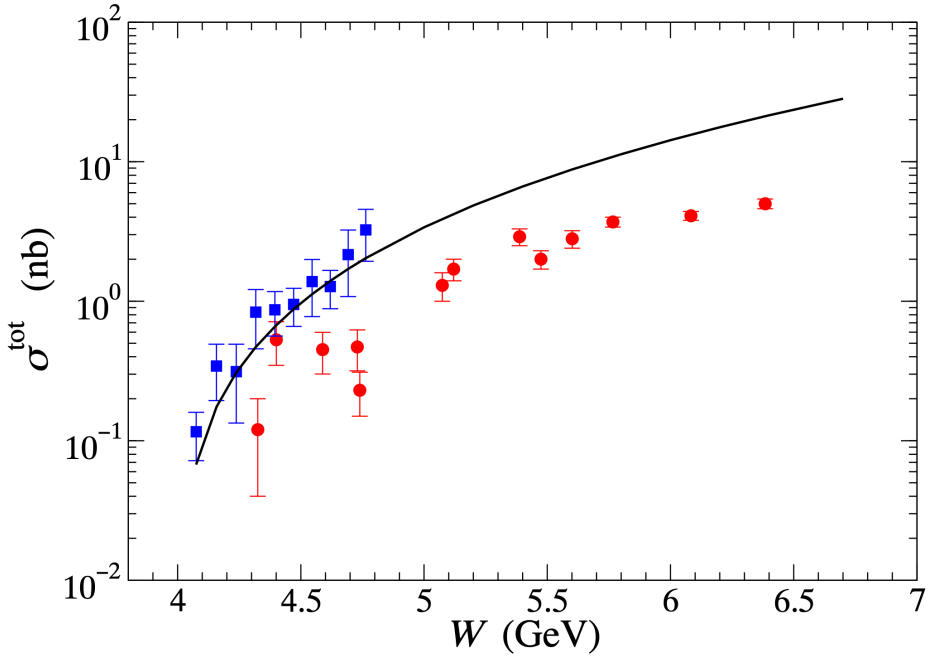
$$G^{(0)}(t, \xi) = \frac{1}{\xi^2} \int_{-1}^{1} dx \, F_g(x, \xi, t),$$

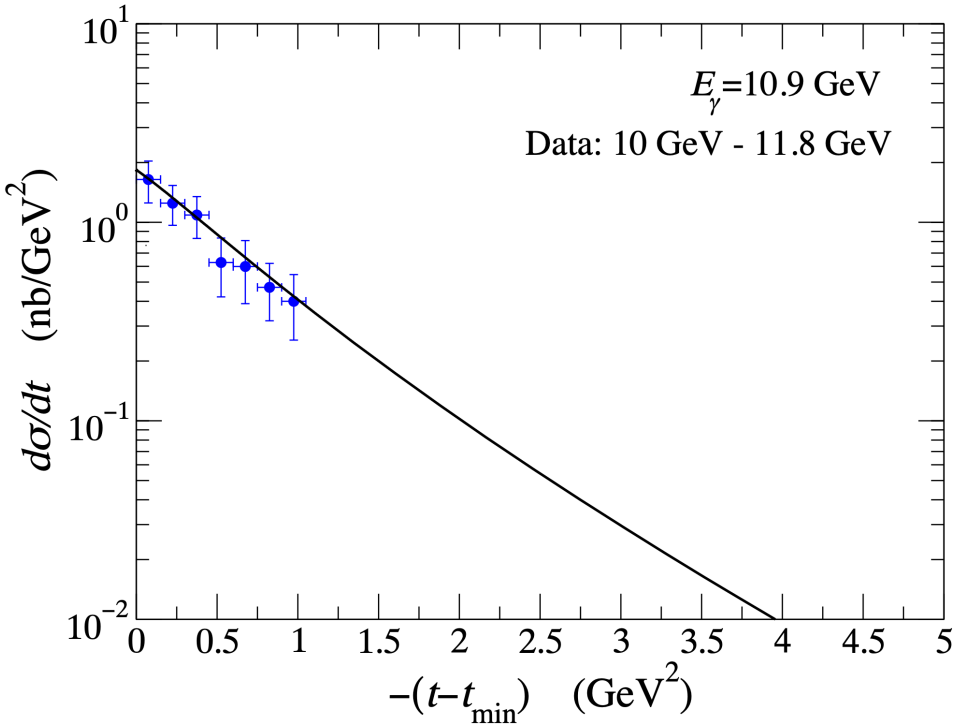
- ✓ The differential cross section becomes schematically

$$\frac{d\sigma}{dt} \propto \alpha_{\mathrm{em}} \, \alpha_s^2 \, | \phi_{J/\psi}(0) |^2 \, | G^{(0)}(t, \xi) |^2 .$$



Near- threshold models: GPD-based model





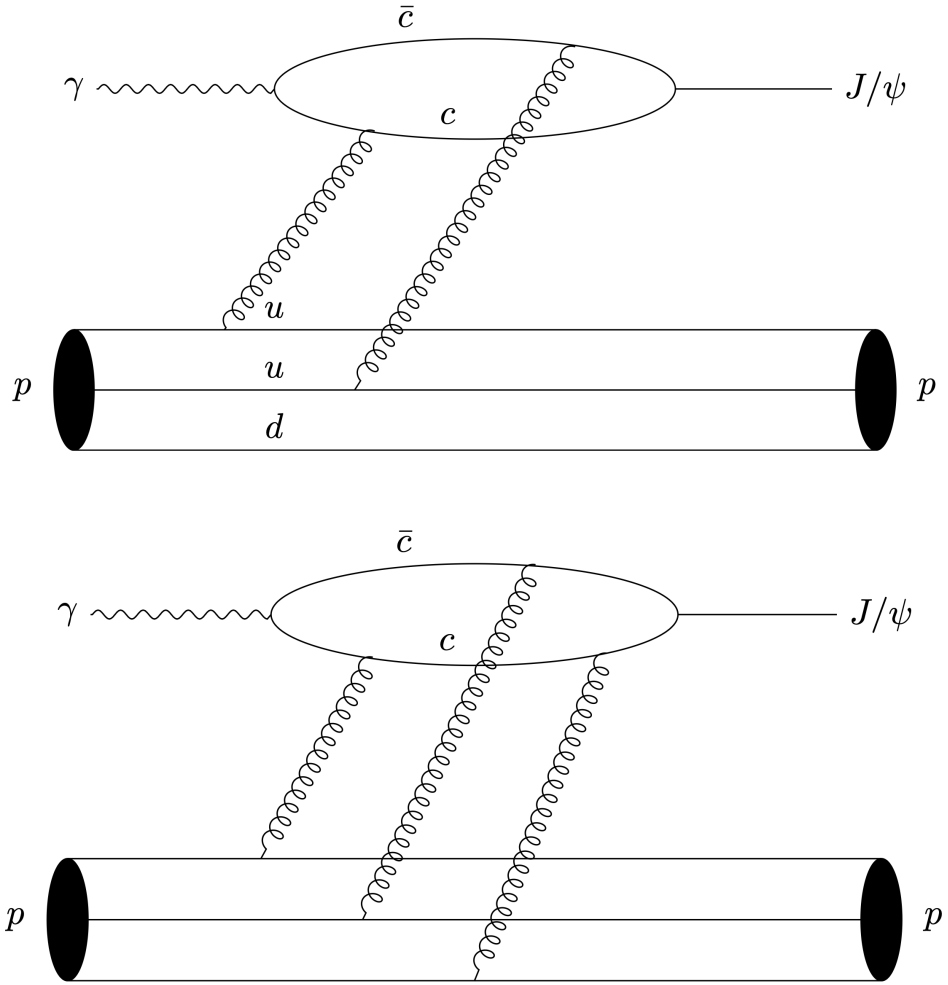
✓ total cross section

✓ differential cross section

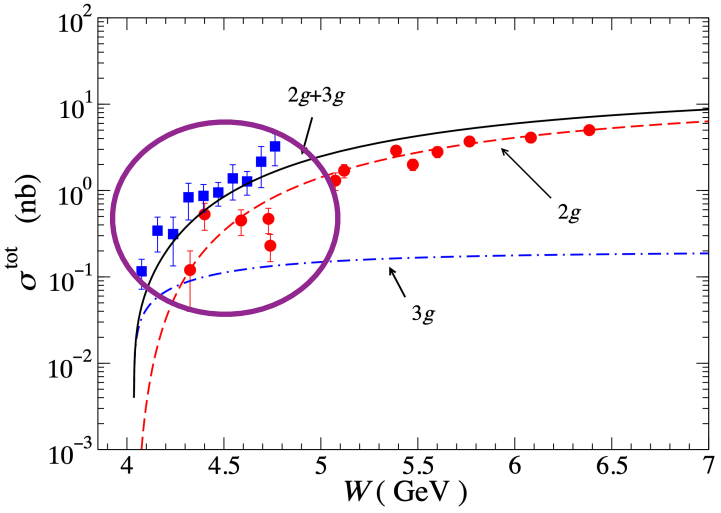
✓ The GPD is taken from the LQCD calculation, and one chooses the dipole parameterization for the gravitational form factor.

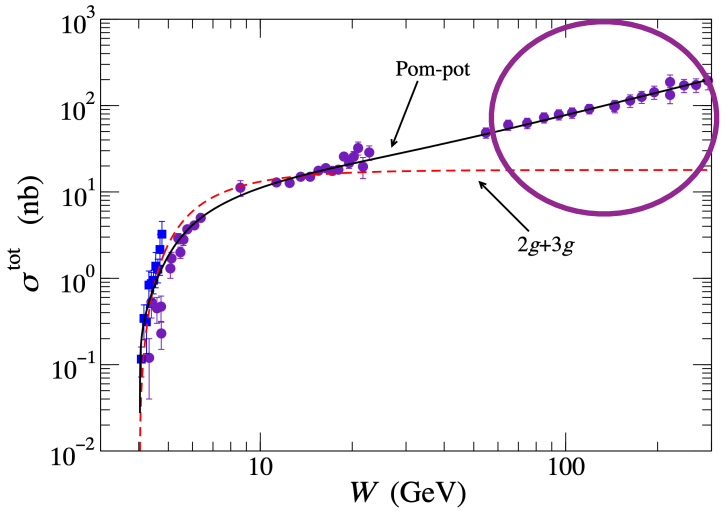
Near- threshold models: 2g +3g model

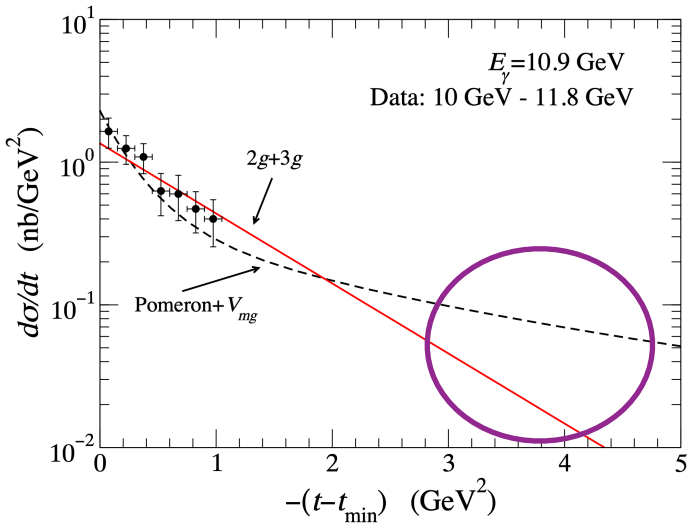
- ✓ The PQCD model to fit the JLab data, assumes that the $\bar{c}c$ scattered from the valance quarks with fraction of momentum $x \sim 1$ of the target nucleus.
- ✓ For the nucleon target, this model has two- and three-gluon exchange processes.
- ✓ 2g +3g model



Near- threshold models: 2g +3g model







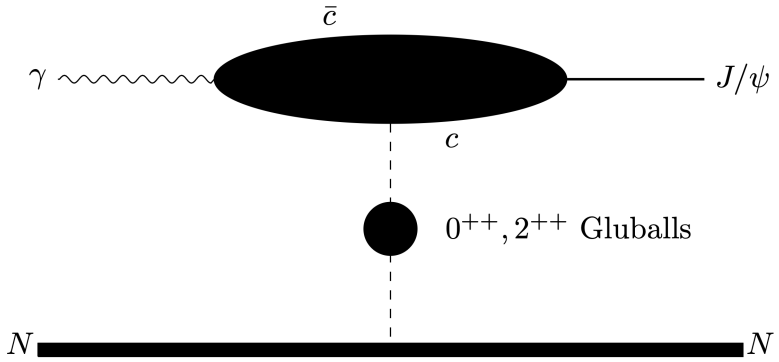
✓ total cross section ✓ total cross section at large W ✓ differential cross section

✓ The old data can be fitted by the two-gluon exchange 2g model. The JLab data can be fitted by adding the 3g exchange contribution.

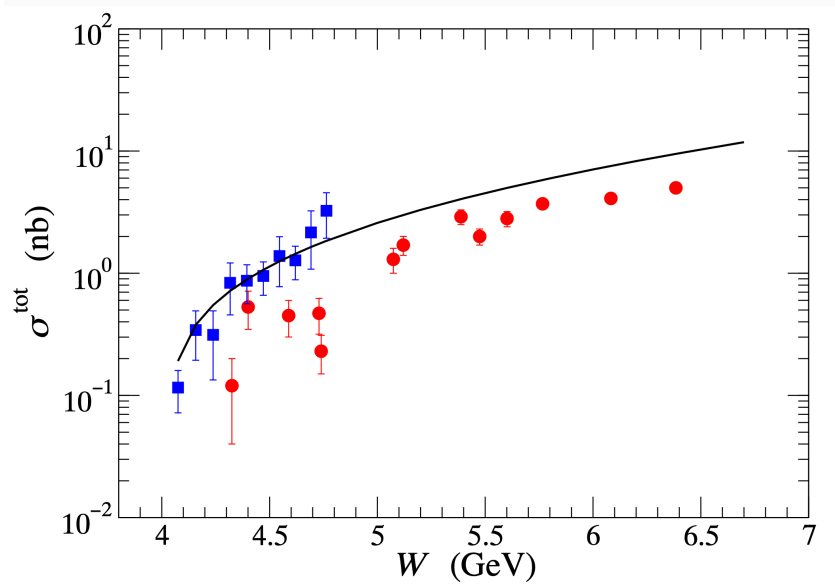
✓ The main difference between the Pomi-pot model and the 2g +3g model is at high energies.

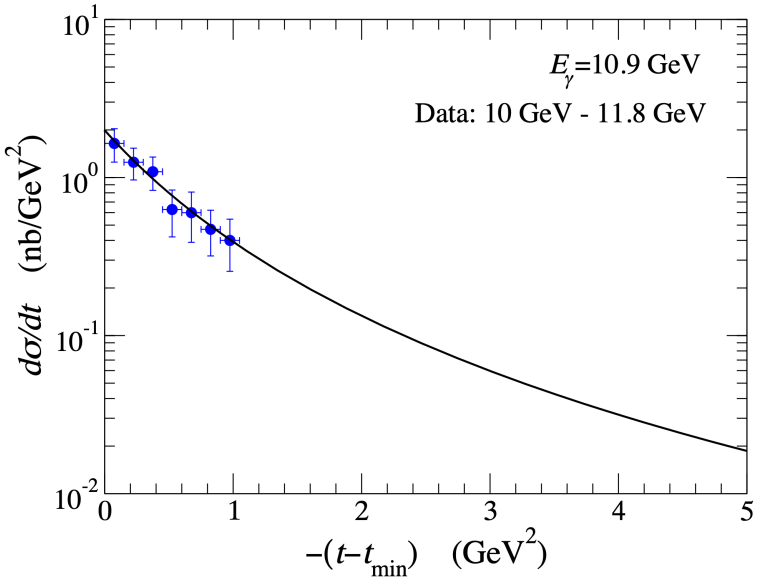
✓ Their difference can also be distinguished in differential cross sections at large t.

holographic formulation model



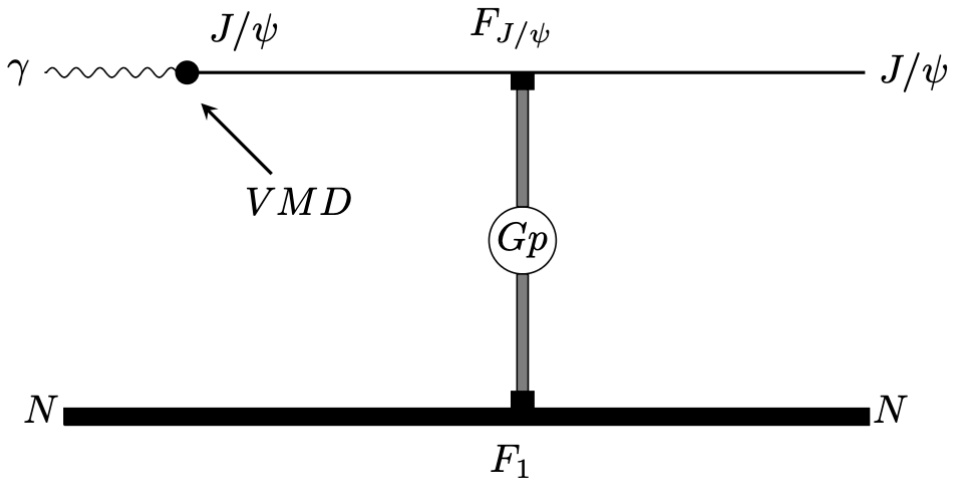
✓ This model assumes that the $\gamma + p \rightarrow J/\psi + p$ is due to the exchanges of tensor (2++) and scalar (0++) glueballs



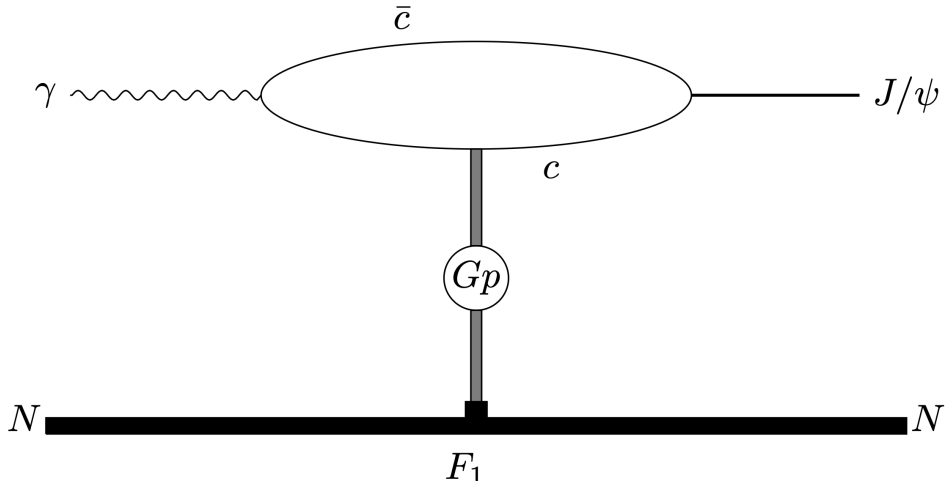


✓ The results for total cross section and differential cross section are consistent with with the JLab data.

Pomeron-exchange model: replacing the VMD assumption with a constituent quark-loop mechanism (P-CQM)



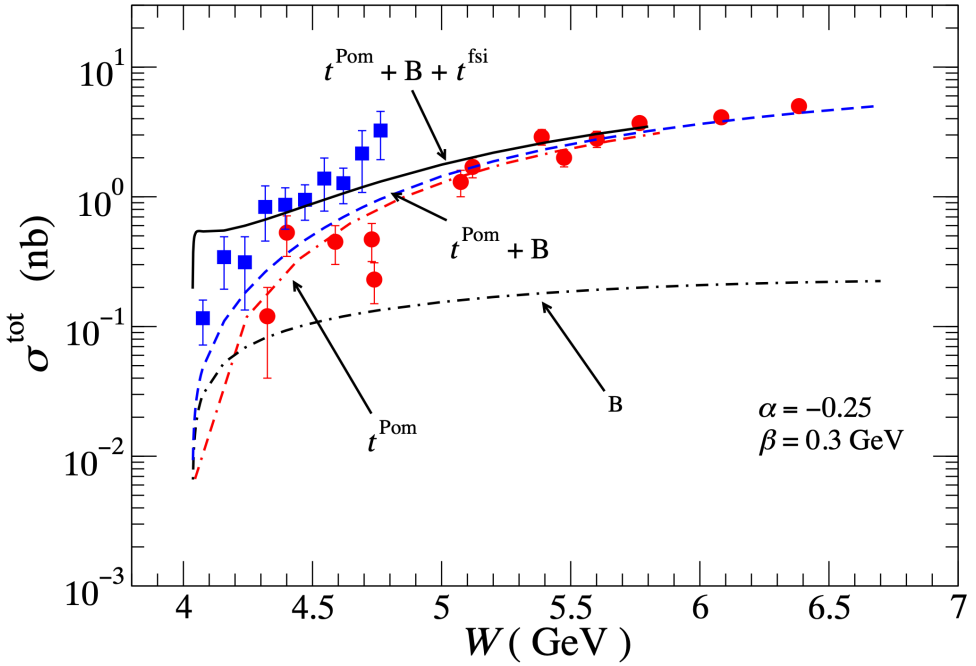
replace the VMD assumption the by constituent quark-loop mechanism



✓ Use the constituent quark model (CQM) to evaluate the $\bar{c}c$-loop

Pomeron-exchange model: replacing the VMD assumption with a constituent quark-loop mechanism (P-CQM)

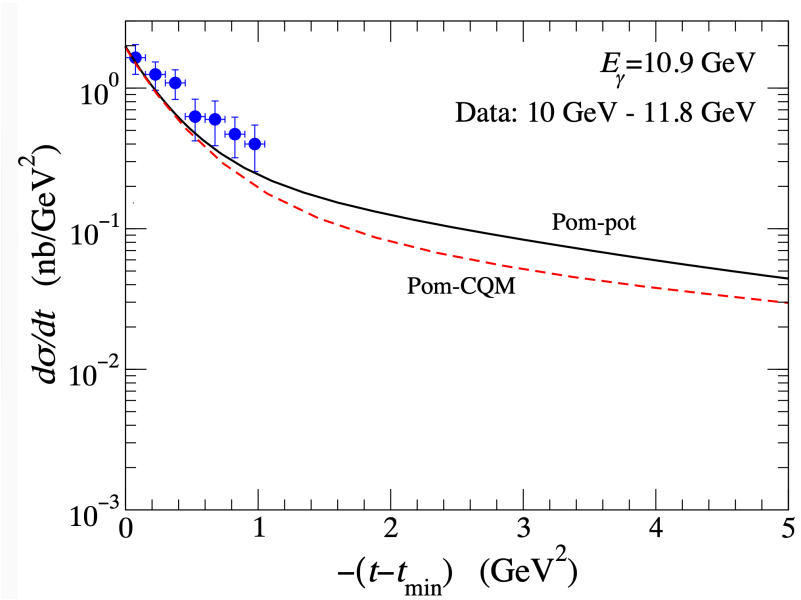
- ✓ The Born term (B, charm-N potential) is larger than the Pomeron-exchange (t^{Pom}) near threshold.
- ✓ When the Pomeron-exchange is included (t^{Pom}+B), the predicted results are still below the Jlab data.
- ✓ Only when FSI effects (at very near threshold) are included (t^{Pom} +B +t^{fsi}), the result agrees reasonably with the JLab data.
- ✓ The available JLab data for total cross section can be reasonably fitted by the all models.

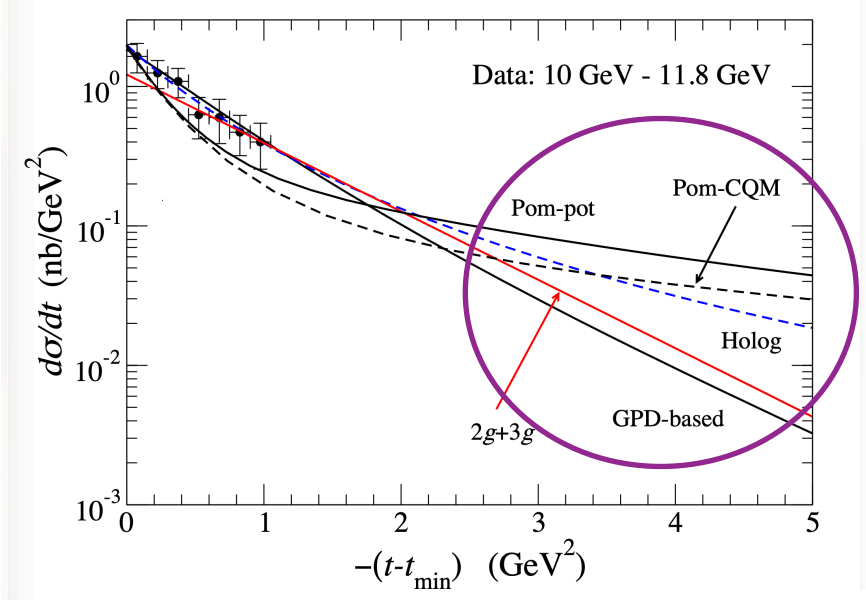


✓ total cross section

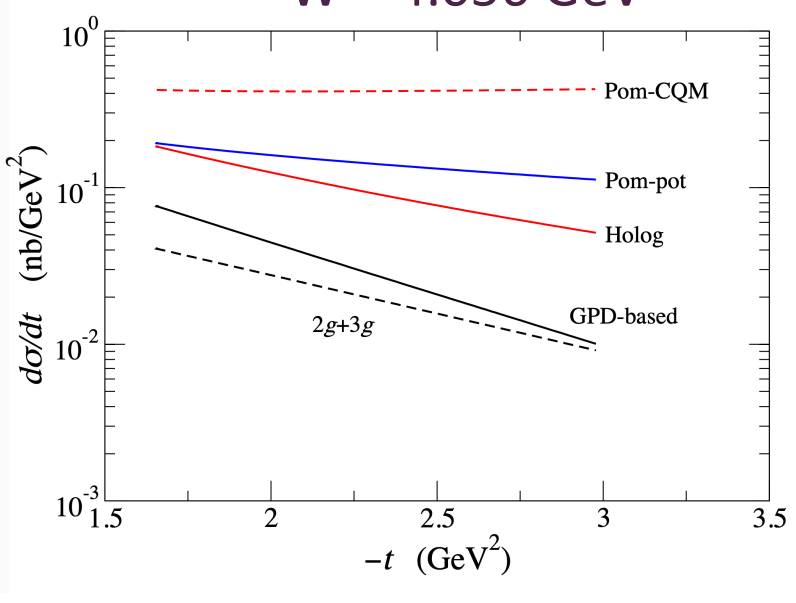
Pomeron-exchange model: replacing the VMD assumption with a constituent quark-loop mechanism (P-CQM)

✓ Differential cross section





W = 4.056 GeV



✓ Distinguishing between these models requires more extensive data from future experiments, particularly differential cross sections at large |t|.

✓ The differences between models become especially pronounced near threshold, at W = 4.056 GeV.

Pomeron-exchange model: replacing the VMD assumption with a dynamically dressed QCD quark-loop mechanism (P-dyn)

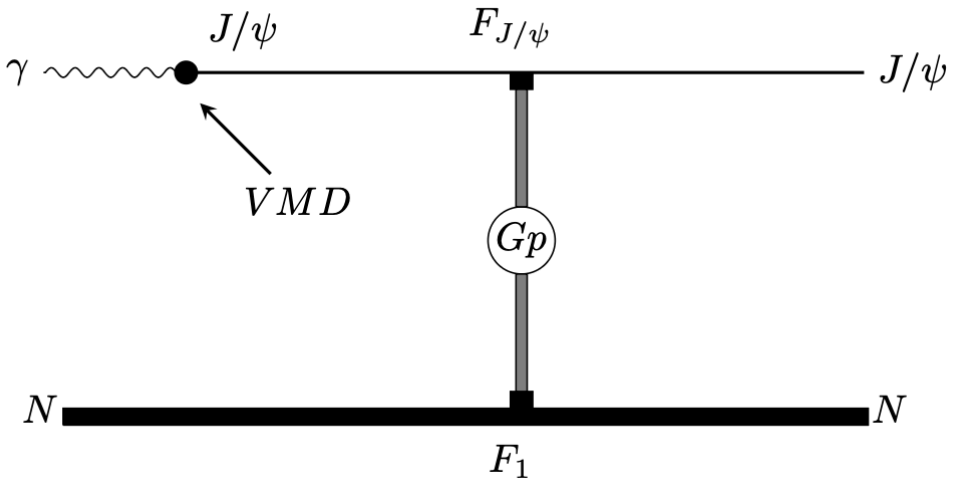
➢ In Pom-CQM,

- ✓ J/ψ is described using constituent charm quarks with a simple s-wave Gaussian wave function; the width parameter is fitted to $J/\psi \to e^+e^-$.
- ✓ charm-N interaction is modeled phenomenologically, e.g. with a Yukawa-type potential.

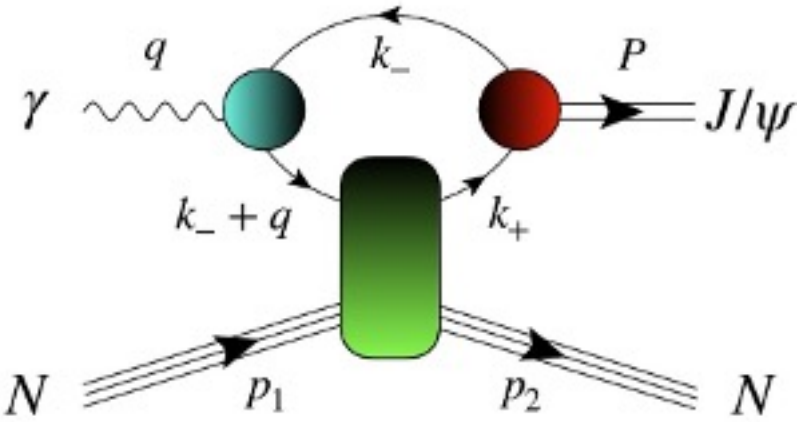
➢ In Pom-dyn,

- ✓ Quark propagators are momentum-dependent and dynamically dressed
- ✓ Vector meson is represented by a covariant Bethe–Salpeter amplitude
- ✓ Photon couples through the quark-level electromagnetic vertex
- ✓ Hence the quark loop has genuine QCD momentum dependence rather than a constituent mass plus model wave function.

P-dyn



replace the VMD assumption the by dynamical quark-loop mechanism



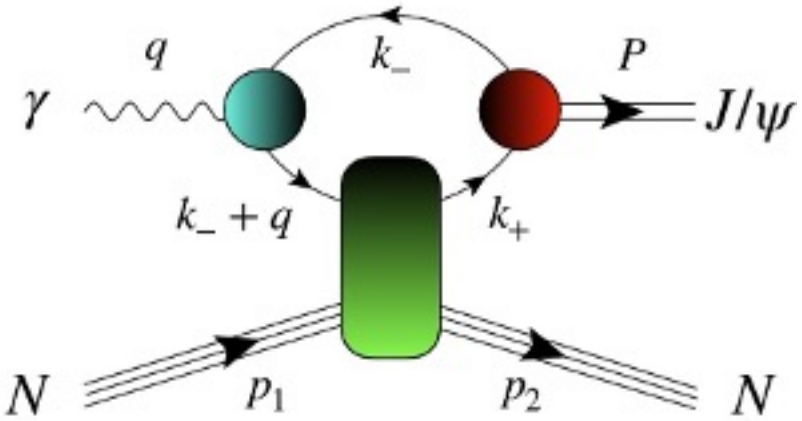
- ✓ HERA era: How do we move from soft to hard QCD?

  Compare $\rho, \phi, \omega, J/\psi, \Upsilon$

- ✓ Is there an approach that can provide an unified description of photoproduction of vector mesons ($V = \rho, \phi, \omega, J/\psi, \Upsilon$) from their respective thresholds up to very high energies?

P-dyn

➢ $\gamma + p \rightarrow V + p$: a reaction model where the process is dynamically resolved into three core stages



✓ 1. Photon Fluctuation:

incoming photon fluctuates into a (virtual) $\bar{q}q$ pair

✓ 2. Diffractive Scattering:

$\bar{q}q$ pair interacts with proton via exchange of Pomeron

✓ 3. Meson Formation:

$\bar{q}q$ subsequently coalesces into the final-state, on-shell vector meson

P-dyn

➢ The Dynamical Transition Amplitude：

$$t^V_{\mu\alpha\nu}(q,P) = e_V N_c \,\mathrm{tr}_D \int \frac{d^4k}{(2\pi)^4} S_q(k_-)\,\Gamma^\gamma_\mu(k_-, k_- + q)\, S_q(k_- + q)\,\Gamma^{\mathbb{P}}_\alpha(k_- + q, k_+)\, S_q(k_+)\,\Gamma^V_\nu(k_+, k_-)$$

➢ The ingredients are: $S_q(k)$: dressed-quark propagator, Γ^γ_μ : dressed photon-quark vertex, $\Gamma^{\mathbb{P}}_\alpha$: Pomeron-quark vertex ($\Gamma^{\mathbb{P}}_\alpha = \beta_q\,\gamma_\alpha$), Γ^V_ν : vector-meson Bethe-Salpeter amplitude, which are computed using Continuum Schwinger Methods in Qin-Chang gluon interaction and rainbow ladder truncation.

➢ Full photoproduction matrix element

$$\mathcal{J}_\mu(W,t) = 2\, t^V_{\mu\alpha\nu}(q,P)\,\epsilon^\lambda_\nu(P)\,\bar{u}(p_2)\,\widetilde{G}_\alpha(w^2,t)\,u(p_1)$$

$$\widetilde{G}_\alpha(w^2,t) = \gamma_\alpha F_0(t)\, 3\beta_\ell\, G_{\mathbb{P}}(w^2,t)$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi^2}\frac{m_p}{4W}\frac{|\vec{P}|}{k_W}\frac{1}{2}\sum_{\text{proton spin}}\left(|\mathcal{J}_1|^2 + |\mathcal{J}_2|^2\right)$$

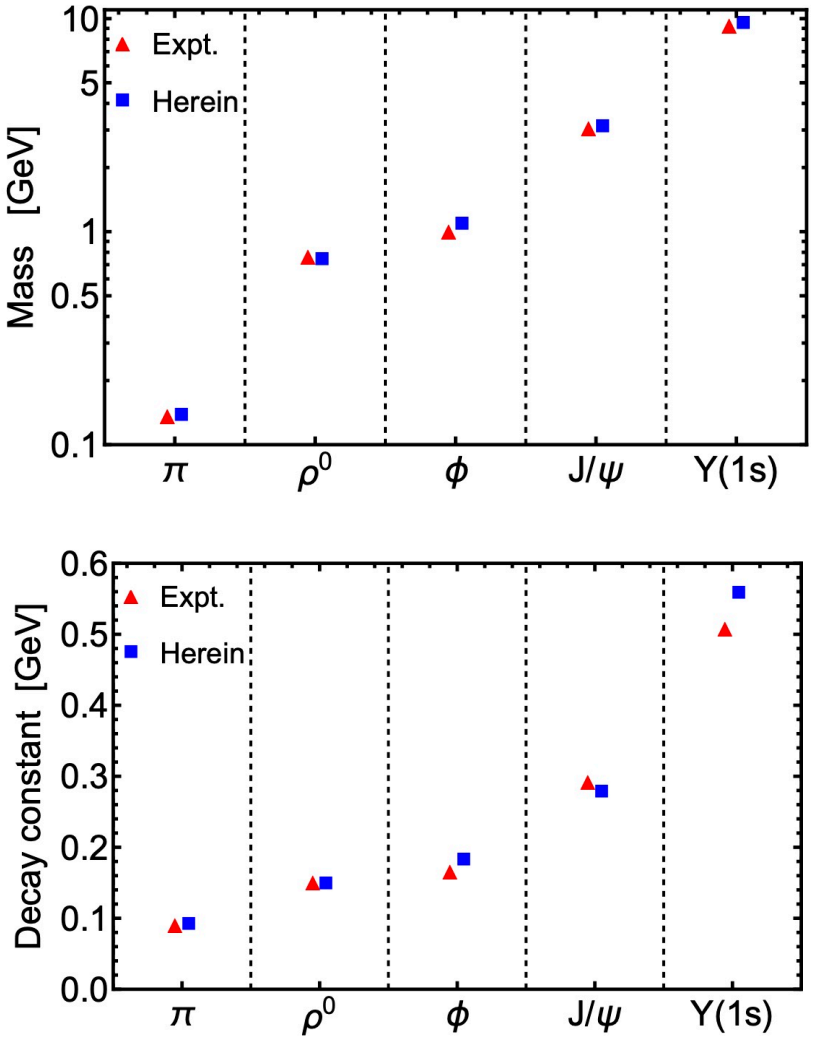
L. Tang et al., Phys. Lett. B 856 (2024) 138904

L. Tang et al., Eur. Phys. J. C 86 (2026) 3, 284

P-dyn: vector meson properties

✓ We deliver a good description of a range of vector meson static properties (masses, decay constants).

Meson	Mass [GeV]		Decay constant [GeV]	
	Herein	Expt.	Herein	Expt.
π	0.138	0.138	0.092	0.092
ρ^0	0.741	0.775	0.149	0.153
ϕ	1.086	1.019	0.183	0.168
J/ψ	3.123	3.097	0.278	0.294
$\Upsilon(1s)$	9.52	9.46	0.558	0.51



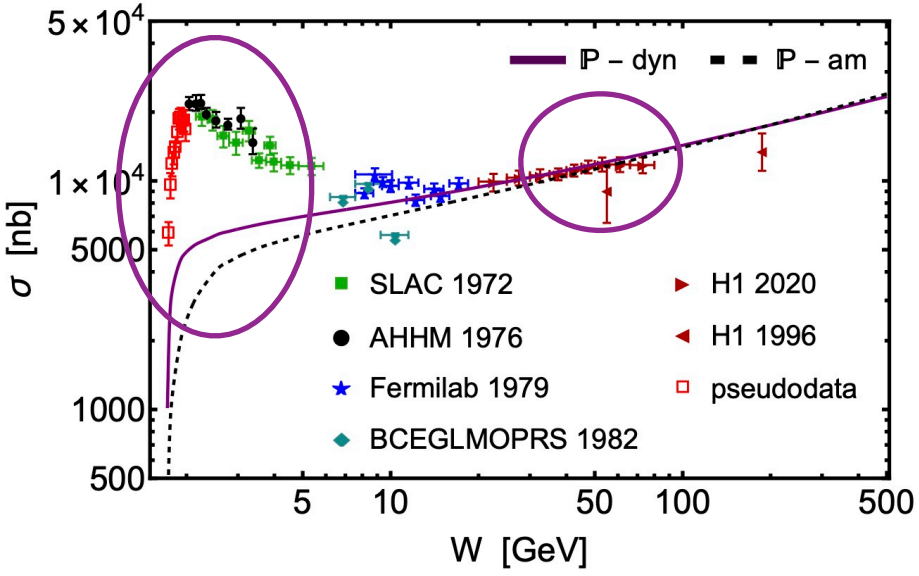
P-dyn: parameters

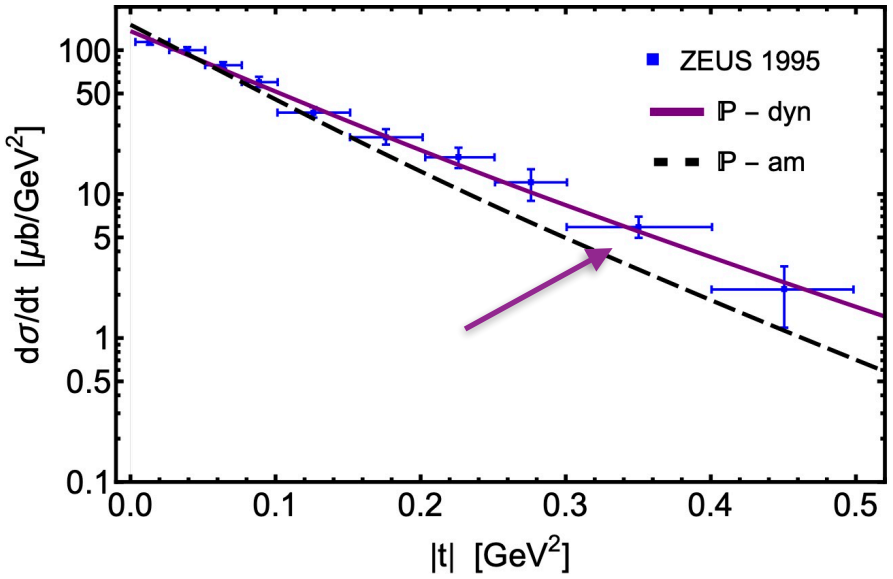
Meson	Gluon model					$\mathbb{P}$ trajectory		$\mathbb{P}$-dyn	$\mathbb{P}$-am
	$m_{\zeta_{19}}$ [GeV]	$D\omega$ [GeV^3]	ω [GeV]	N_f	$\Lambda_{\rm QCD}$ [GeV]	α_0	α_1 [GeV^{-2}]	β_q [GeV^{-1}]	β_q [GeV^{-1}]
ρ^0_ℓ	0.0034	0.8^3	0.5	4	0.234	1.1	0.33	3.5	1.96
ϕ_s	0.083	0.8^3	0.5	4	0.234	1.1	0.33	1.89	1.51
J/ψ_c	0.89	0.6^3	0.8	4	0.234	1.2	0.115	0.11	0.428
Υ_b	3.59	0.6^3	0.8	5	0.36	1.2	0.115	0.016	0.638

- ✓ Light mesons (ρ, ϕ): $\alpha_0 = 1.1, \alpha'_P = 0.33\ \text{GeV}^{-2}$
- ✓ Heavy mesons ($J/\psi, \Upsilon$): $\alpha_0 = 1.2, \alpha'_P = 0.115\ \text{GeV}^{-2}$
- ✓ Only the Pomeron-quark couplings β_q are free parameters. Each β_q is determined by a fit to the high-energy (W > 10 GeV) data for its respective meson.
  - $\beta_{(u/d)}$... fixed by HERA high-W $\gamma p \to \rho^0 p$ differential cross-section
  - β_c ... fixed by HERA high-W $\gamma p \to J/\psi p$ forward differential cross-section
  - β_s... fixed by ZEUS high-W $\gamma p \to \phi p$ total cross-section
  - β_b ... fixed by ZEUS and LHCb high-W $\gamma p \to \Upsilon p$ total cross-section

P-dyn: results for $\gamma + p \to \rho + p$

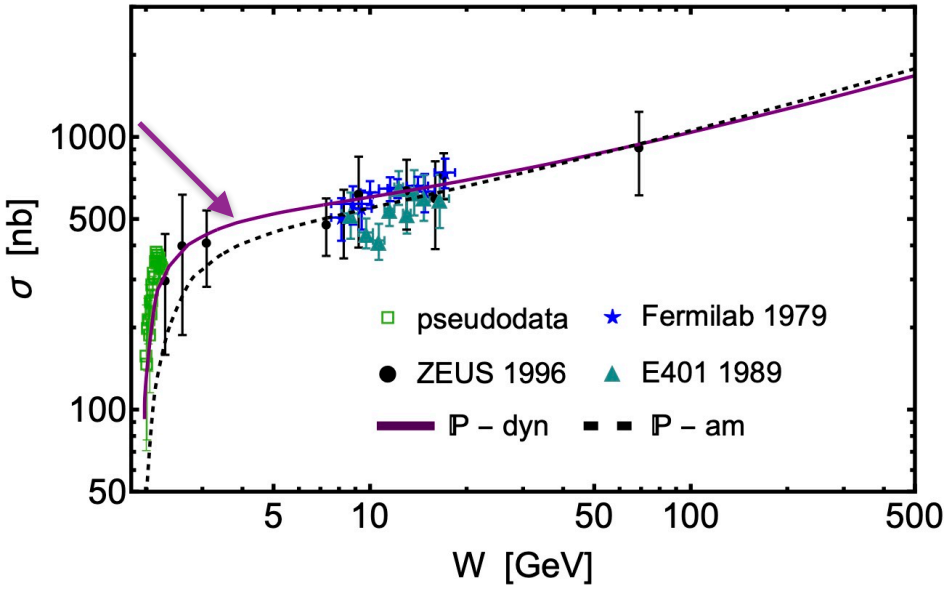
- Total cross section, both P-dyn and P-am reproduce the data on $W \geq 10$ GeV, the domain of Pomeron dominance.
- However, both models are equally poor on $W < 5$ GeV, because the proton and ρ meson share valence quarks; allowing additional (non-diffractive) exchange contributions.
- Differential cross section, data is in 60 < W < 80 GeV, our results are at W= 70 GeV. Quark-loop dynamics remain important on the differential cross section even far above threshold. Similar conclusions hold for ω-meson photoproduction.

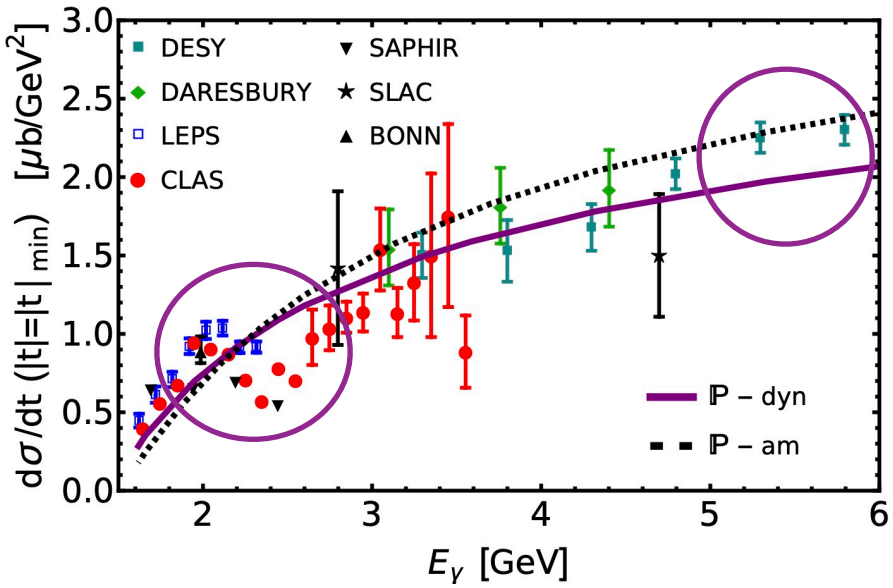




P-dyn: results for $\gamma + p \to \phi + p$

- The ϕ meson ($\bar{s}s$) shares no valence quarks with the proton, so fewer nondiffractive processes contribute.
- P-dyn describes the data much better than P-am, especially near threshold.
- Forward-angle ϕ photoproduction differential cross section. P-dyn provides a better overall description than P-am.
- Some structure appear in the lower figure on a domain $E_\gamma \simeq 2.5$ GeV, possibly caused by meson + baryon final-state interactions (FSIs). Diffractive mechanisms alone cannot explain them.



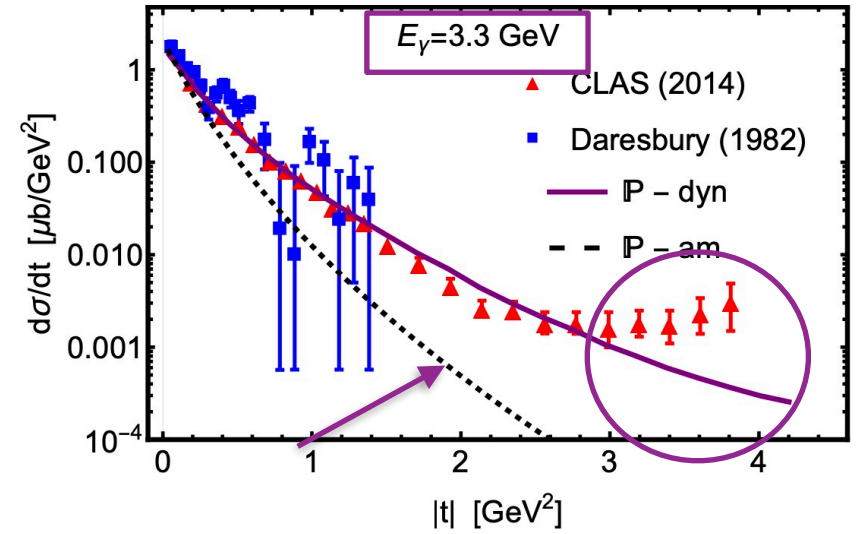


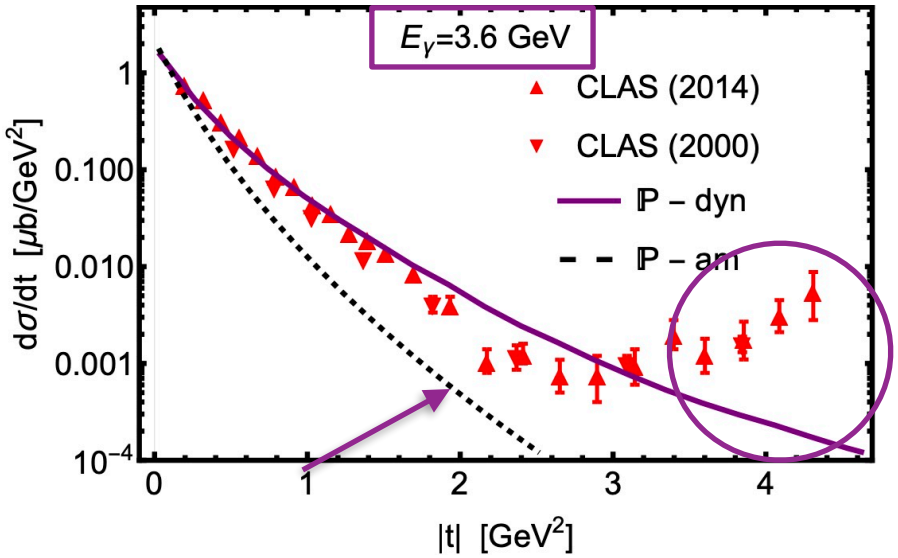
P-dyn: results for $\gamma + p \to \phi + p$

- Differential cross sections: the |t| dependence of ϕ photoproduction is shown at two low photon energies.

- On $|t| \leq 2\,\mathrm{GeV}^2$, P-dyn describes the data well. However, the reaction is not purely diffractive on $|t| > 2\,\mathrm{GeV}^2$: on this domain, one sees structure, likely associated with baryon resonance excitation.

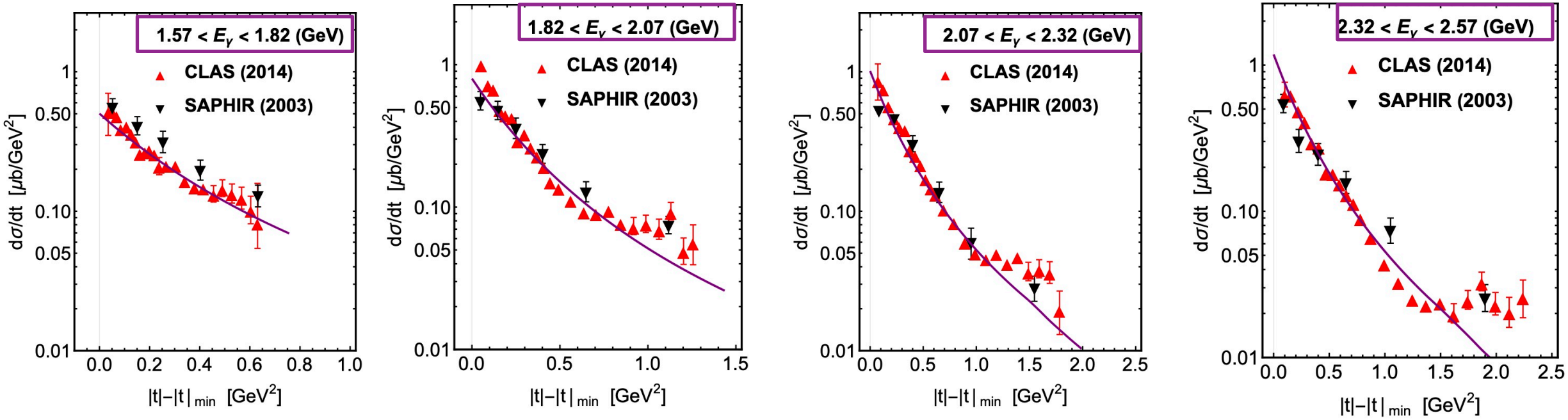
- P-am fails to describe the data across the entire range, highlighting the importance of the quark loop.





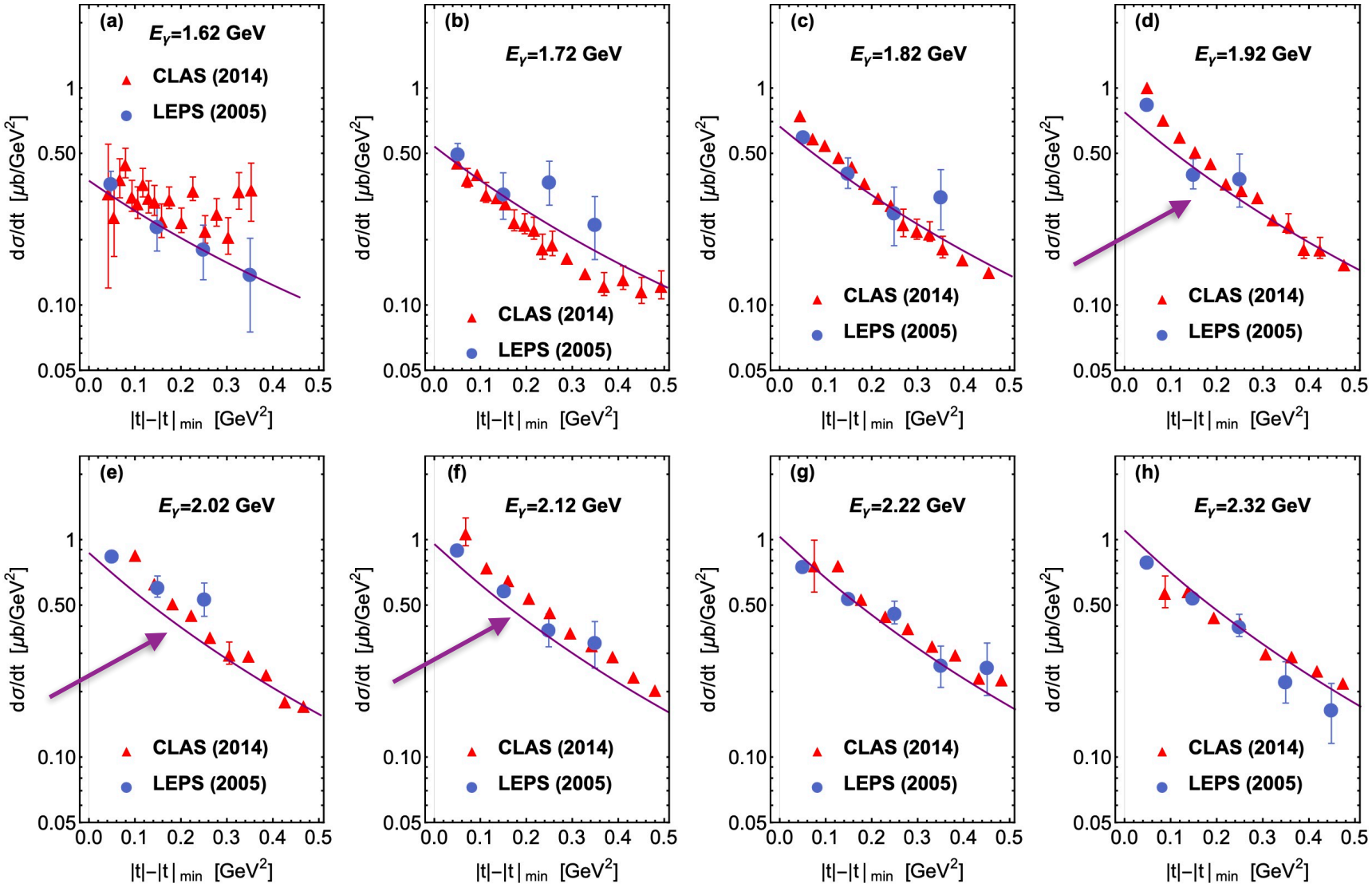
P-dyn: results for $\gamma + p \rightarrow \phi + p$

- Differential cross sections: compare P-dyn results for the |t|-dependence of the ϕ photoproduction with lower photon energies data.
- P-dyn agrees well with data near the forward limit.
- At larger |t|, discrepancies remain, as discussed earlier.



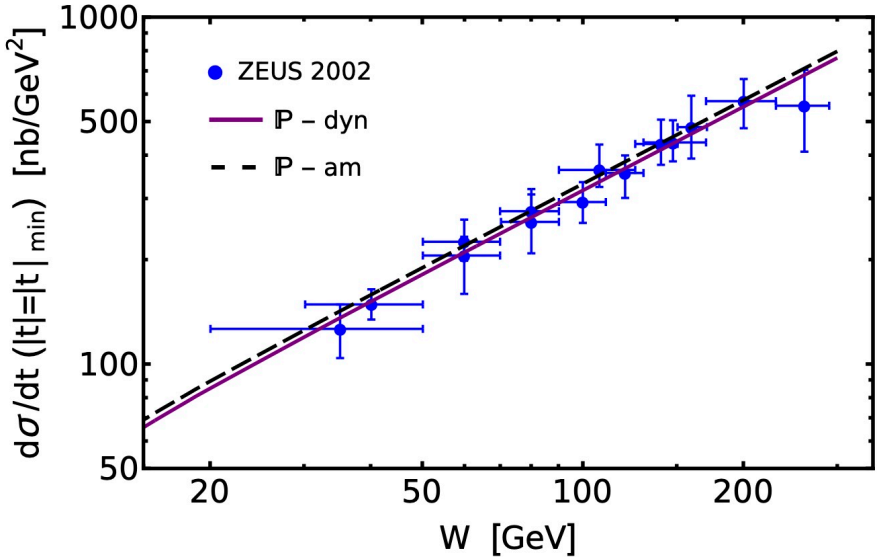
P-dyn: results for $\gamma + p \to \phi + p$

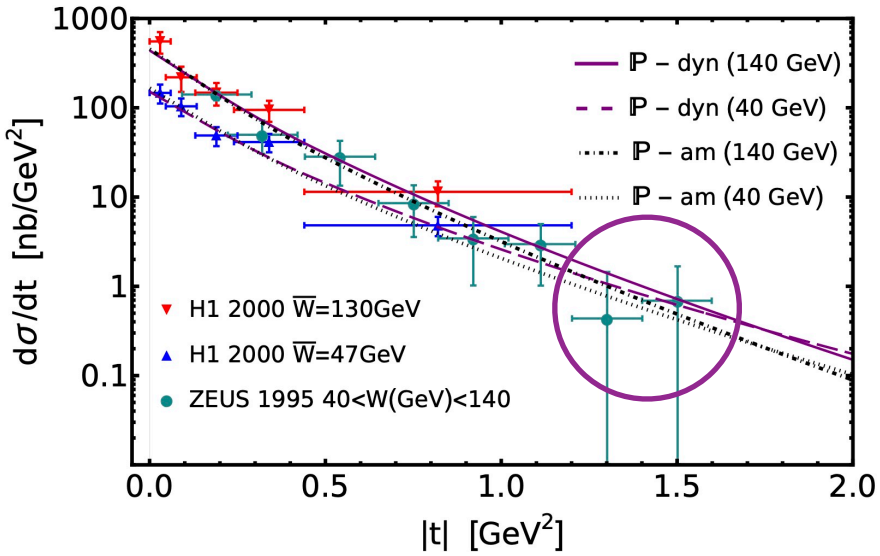
- P-dyn provides a good description of the differential cross section except, perhaps, in the neighbourhood $E_\gamma \simeq 2\text{GeV}$, where upon some nondiffractive processes may be contributing somewhat to the production process.



P-dyn: results for $\gamma + p \to J/\psi + p$

- J/ψ shares no valence quarks with the proton; so photoproduction is dominated by gluon exchange (Pomeron-like processes)
- The Pomeron–charm-quark coupling is fixed using the W -dependence of the differential cross section.
- P-dyn describes the differential cross sections well. Even at high energies, quark-loop dynamics remain important at larger (|t|): compare P-dyn with P-am on $|t| \geq 1\ \mathrm{GeV}^2$.



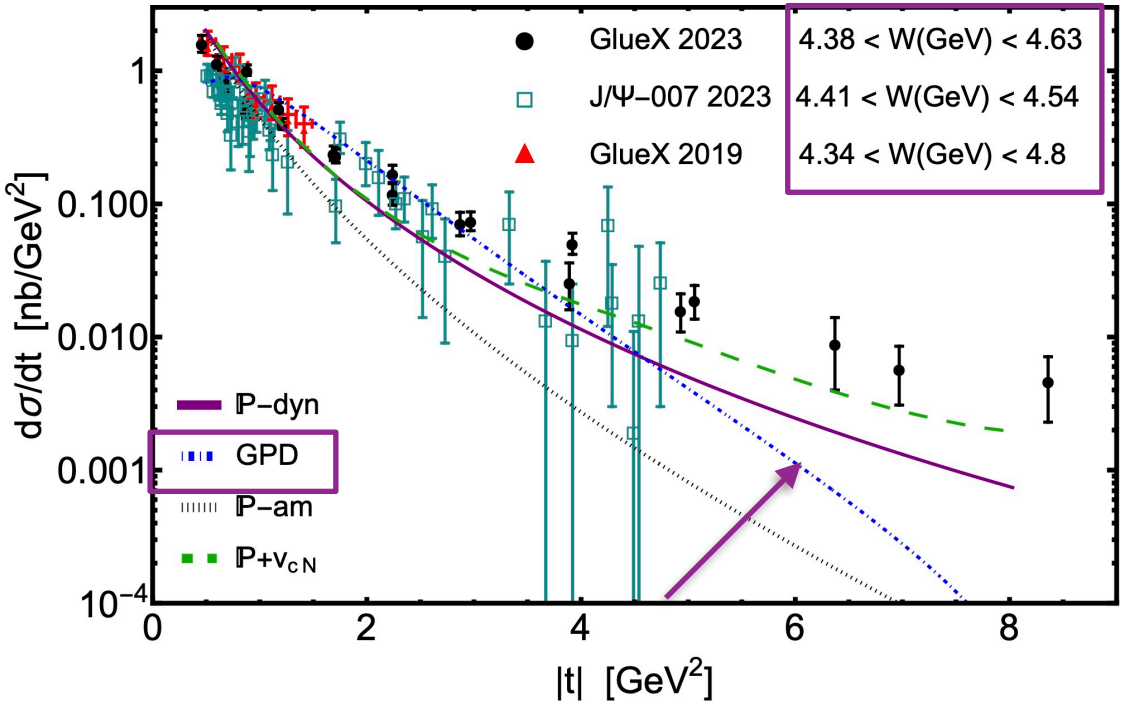


P-dyn: results for $\gamma + p \to J/\psi + p$

- Near threshold, $W_{th}^{J/\psi} = 4.04$ GeV, the (|t|)-dependent differential cross section is sensitive to quark-loop dynamics.

- GPD model: Predicts a concave (|t|) dependence, unlike the decreasing, convex curves of other models. This raises doubts about extracting proton properties using this GPD interpretation.

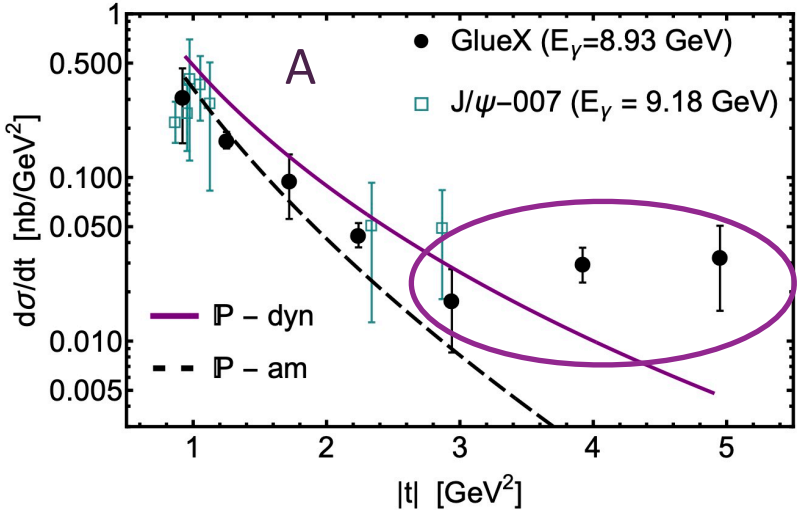
- Pomeron + charm–nucleon potential model: Final-state interactions (FSIs) dominate near threshold. Its predictions resemble P-dyn at small (|t|), $|t| \leq 2.5$ GeV^2, but become harder (decrease more slowly) at larger (|t|).

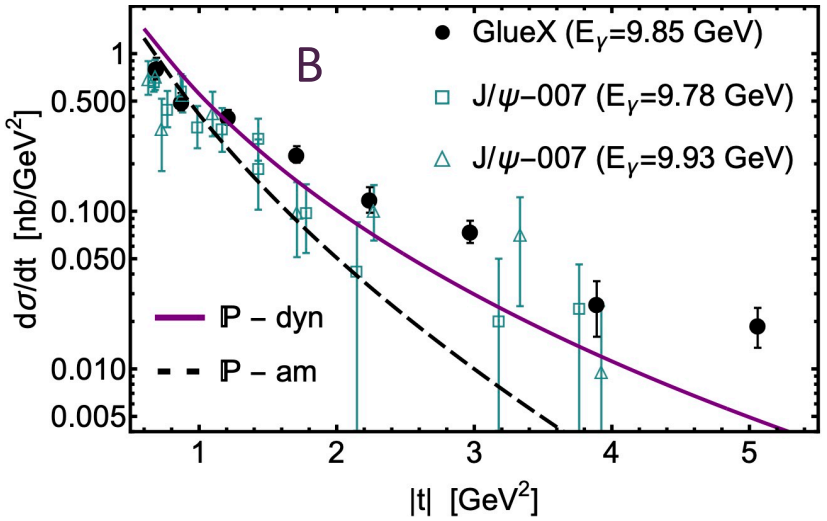


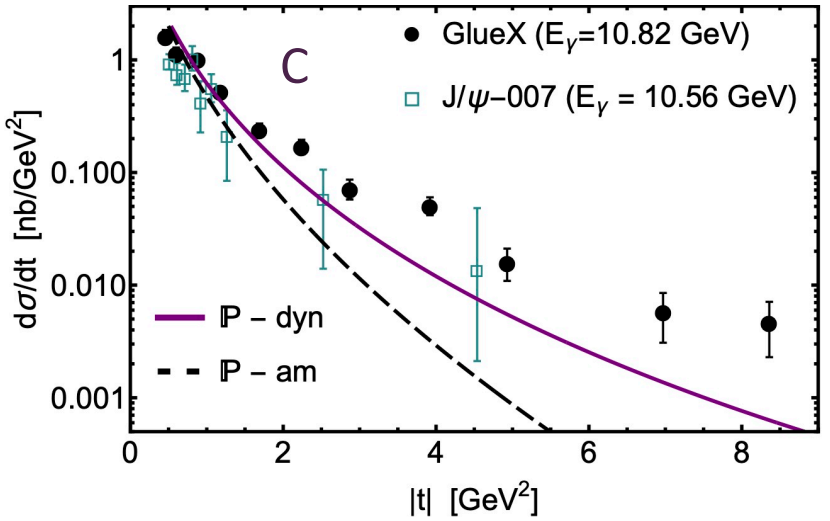
P-dyn: results for $\gamma + p \to J/\psi + p$

- Near threshold (Fig. A): GlueX data suggest possible non-diffractive contributions on $|t| \geq 3\ \mathrm{GeV}^2$, while J/ψ-007 data agree well with P-dyn.

- Figs. B and C: Nondiffractive contributions become less important as energy E_γ increases.

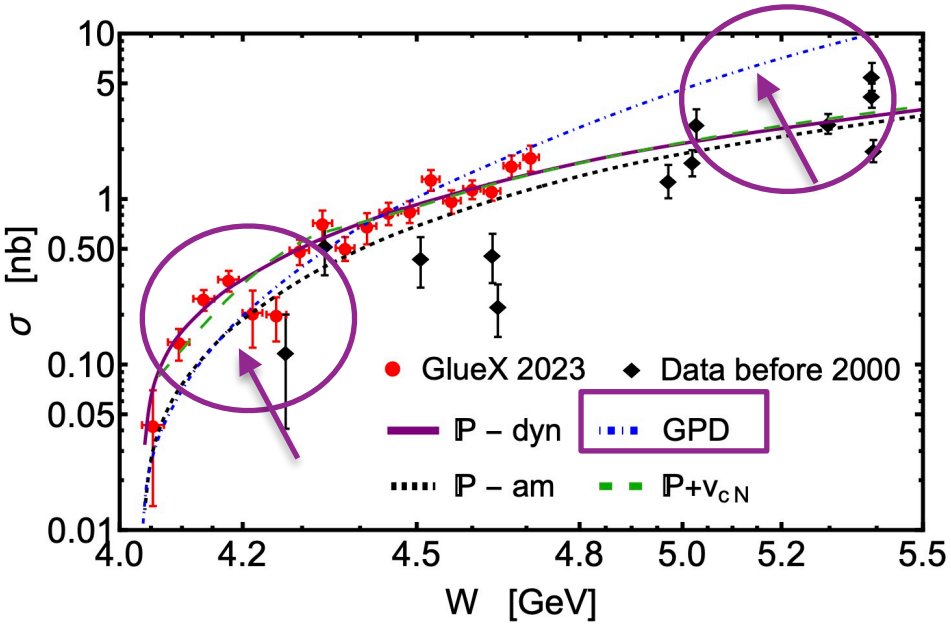


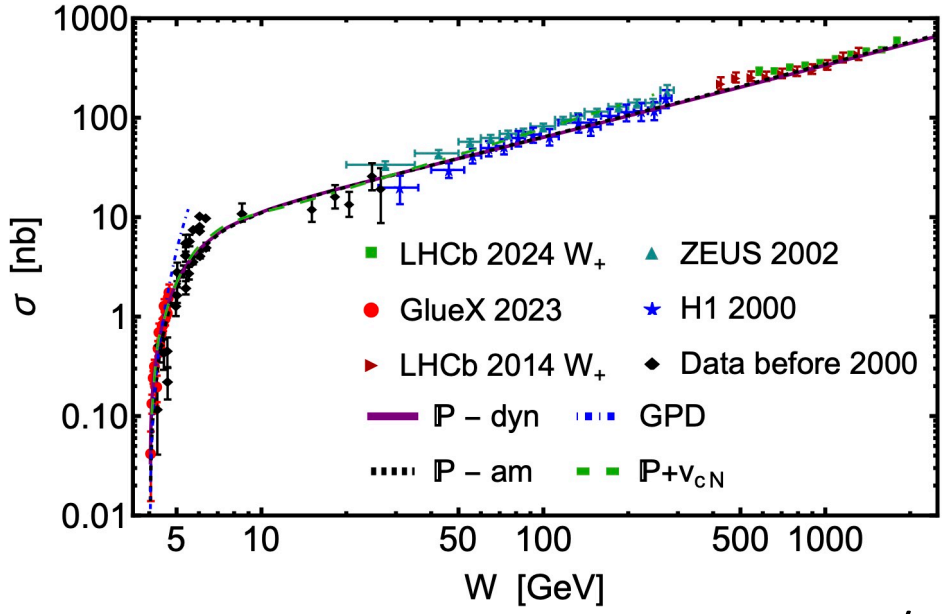




P-dyn: results for $\gamma + p \to J/\psi + p$

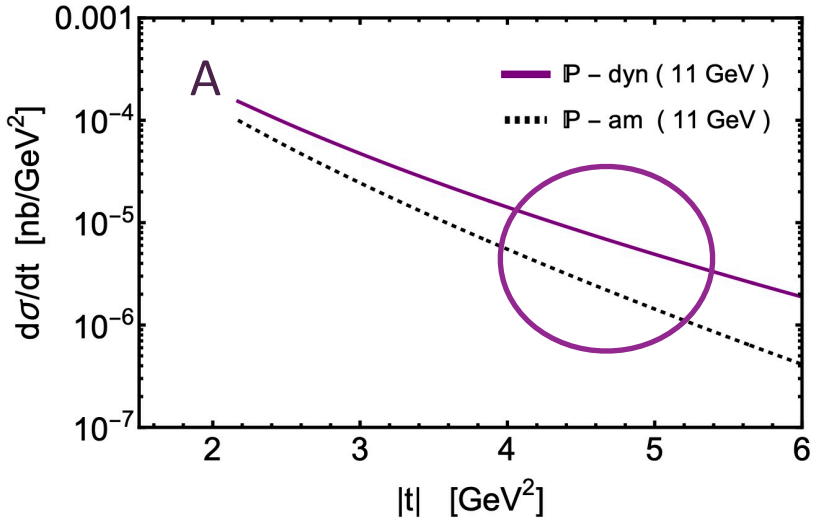
- P-dyn describes all available data well, from threshold to W ≃ 2 TeV.
- P-am model fails near threshold and works only for on W≥5 GeV.
- GPD model, not applicable foron W≥5 GeV.
- Pomeron + ($J/\psi N$) scattering model also describes the total cross-section data well.

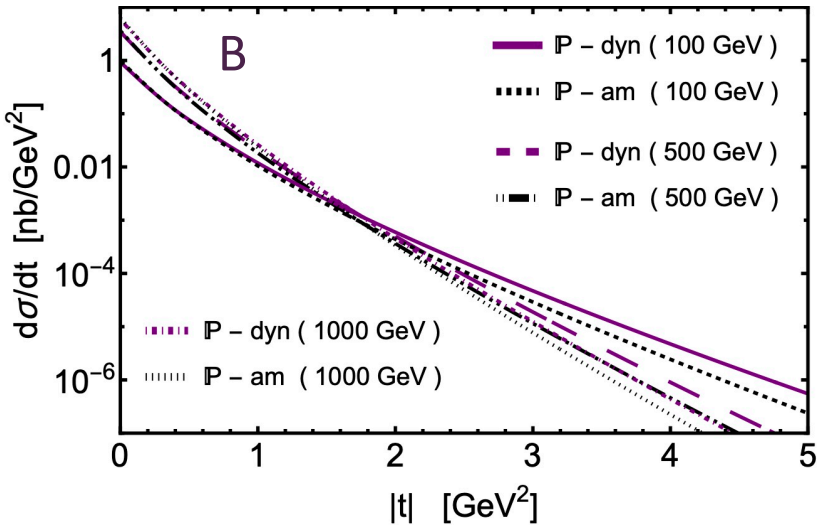




P-dyn: results for $\gamma + p \to \Upsilon + p$

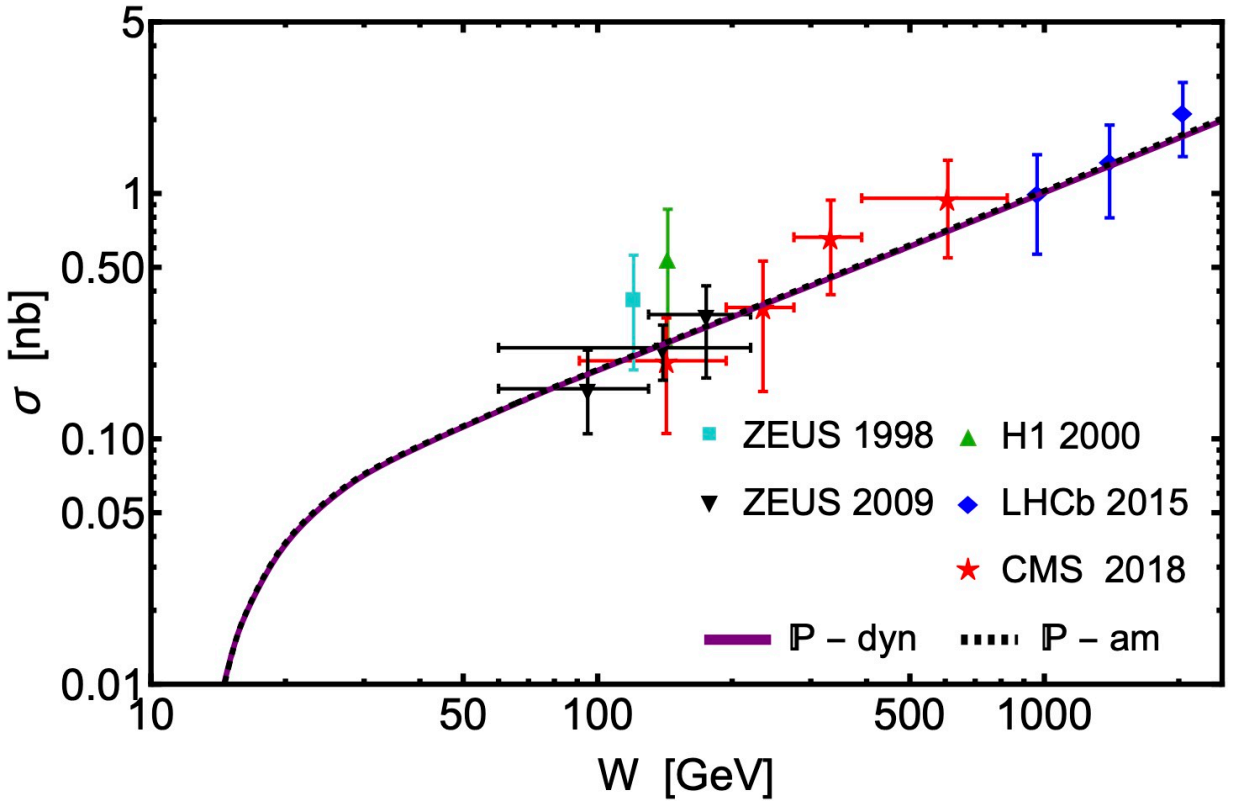
- No differential cross-section data are currently available.
- Fig. A: the dynamical quark loop remains important for Υ photoproduction near threshold.
- Fig. B, with increasing W, the Pomeron trajectory dominates the differential cross section on the diffractive domain.





P-dyn: results for $\gamma + p \to \Upsilon + p$

- Total cross-section data are available only on $100 < W/\text{GeV} < 2000$.
- P-dyn and P-am yield equivalent results; indicating that simple Pomeron exchange is sufficient to describe the existing data.



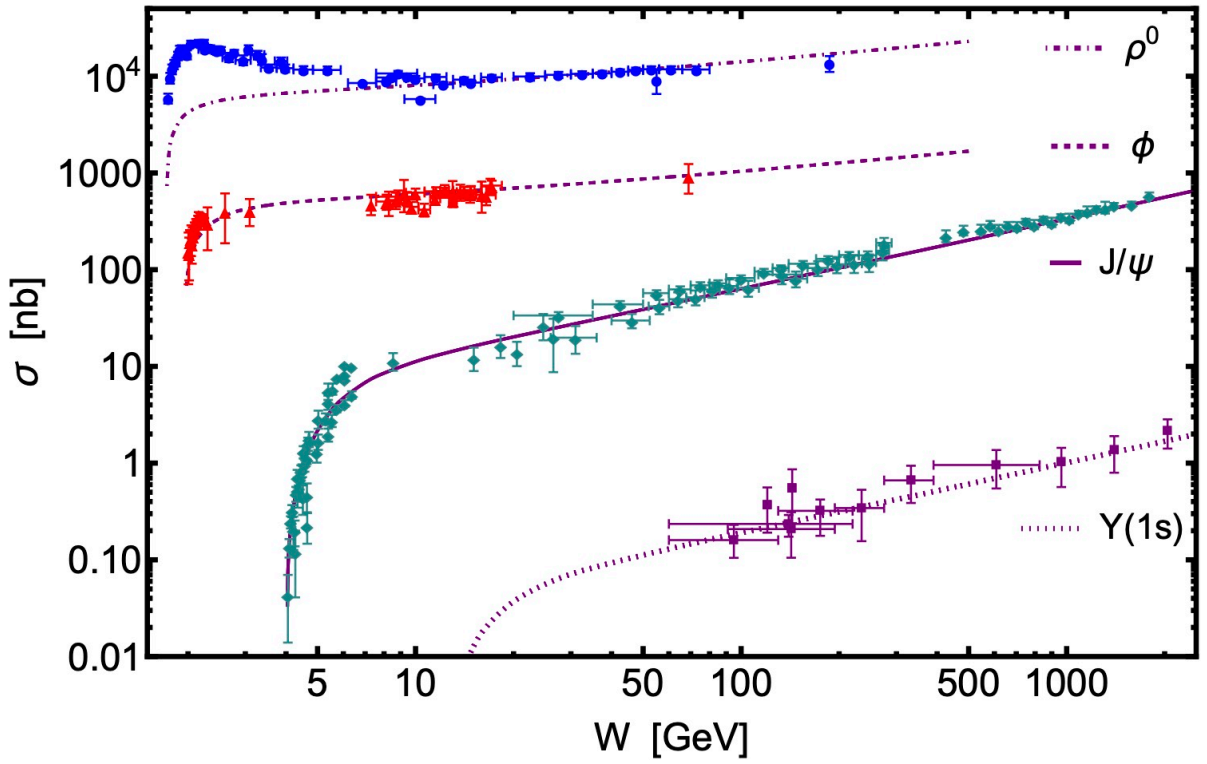
P-dyn: power-law behavior of $\gamma + p \rightarrow V + p$

- Power-law exponents describe the high-energy ((W)) behavior of total cross sections: $\sigma(W) = XW^{\epsilon}$,

$$\sigma(W) = \sigma_P \left[1 - \frac{(m_p + m_V)^2}{W^2}\right]^2 W^{\epsilon}.$$

- Second equation: Valid for all (W); first equation: Valid only well above threshold.

- Comparison with data: The second equation works well for all mesons, while the first works well for heavy mesons.



P-dyn: power-law behavior of $\gamma + p \to V + p$

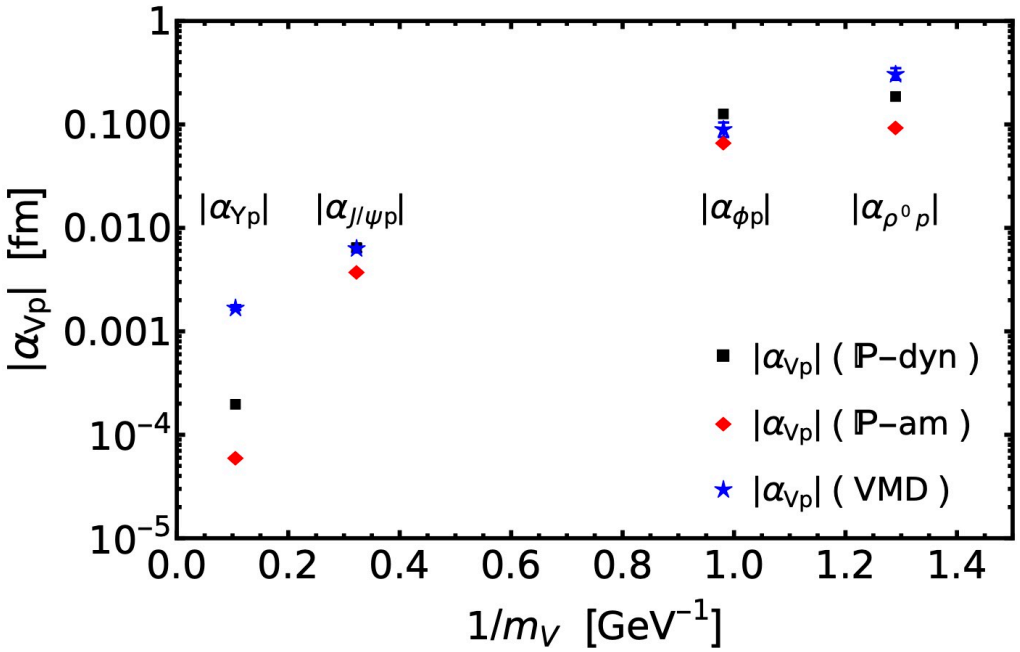
- A: P-dyn
- B: P-am

- Standard Pomeron-alone framework, the exponents are:
  $\epsilon \approx 4[\alpha_{\mathbb{P}}(0) - 1]$ or
  $\epsilon(t_{\min}(W)) \approx 4[\alpha_{\mathbb{P}}(t_{\min}(W)) - 1]$

A	Eq. (27a)		Eq. (27b)		Expt.
V	X/nb	ϵ	σ_P/nb	ϵ	ϵ
ρ^0	4076	0.27	5611	0.21	$0.17 \pm 0.01^{+0.04}_{-0.03}$
ϕ	234.2	0.26	430.0	0.20	$\approx \epsilon_\rho$ [49,126]
J/ψ	2.136	0.73	2.178	0.73	0.67 ± 0.03
Υ	0.0064	0.73	0.0066	0.73	0.77 ± 0.14
B	Eq. (27a)		Eq. (27b)		Expt.
V	X/nb	ϵ	σ_P/nb	ϵ	ϵ
ρ^0	3368	0.32	4151	0.27	$0.17 \pm 0.01^{+0.04}_{-0.03}$
ϕ	268.6	0.30	343.7	0.25	$\approx \epsilon_\rho$ [49,126]
J/ψ	2.099	0.74	2.139	0.74	0.67 ± 0.03
Υ	0.0067	0.74	0.0066	0.73	0.77 ± 0.14

P-dyn: near-threshold slope parameter/vector meson-proton scattering lengths

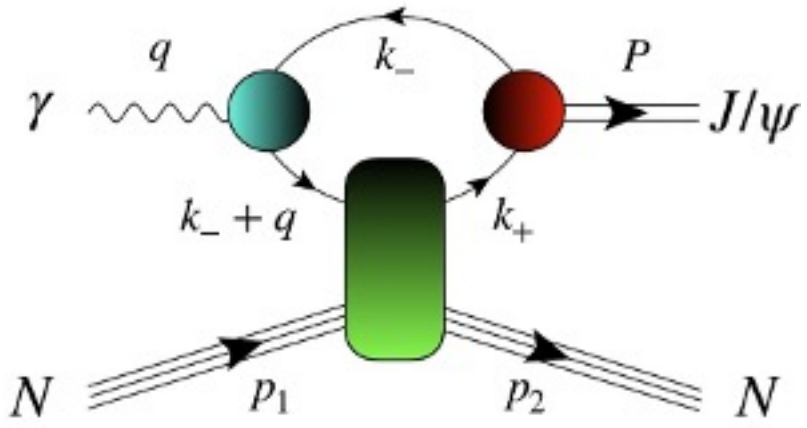
- Within VMD, the near-threshold differential cross section $\gamma + p \to V + p$ is related to the V– p scattering length.
- $|\alpha_{\Upsilon p}| < |\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| < |\alpha_{\rho^0 p}|$
- $|\alpha_{Vp}|$ is not interpret as the V– p scattering length; instead, viewed as a near-threshold slope parameter.



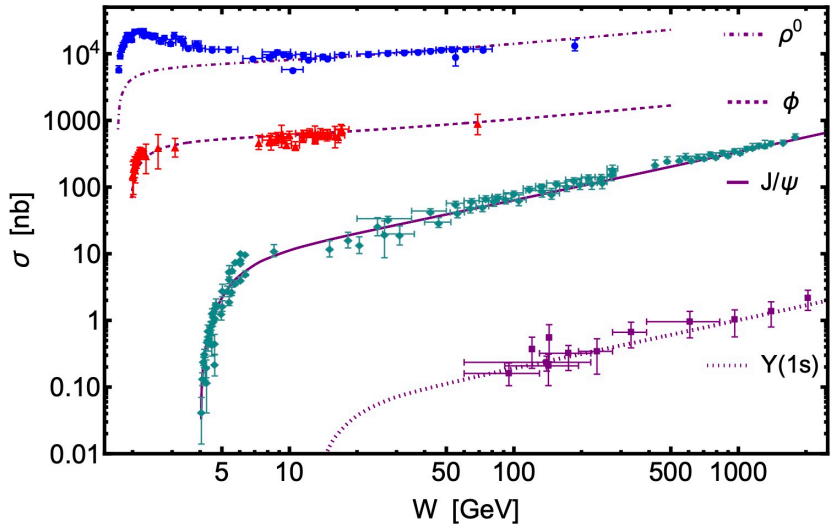
V	m_V/GeV	q_{th}/GeV	$\Gamma_{V\to e^+e^-}$/keV	$\lvert\alpha_{Vp}^{\rm dyn}\rvert$/fm	$\lvert\alpha_{Vp}^{\rm am}\rvert$/fm	$\lvert\alpha_{Vp}^{\rm VMD}\rvert$/fm
ρ^0	0.775	0.6	6.97	0.184	0.097	0.31(04)
ϕ^0	1.019	0.75	1.27	0.123	0.069	0.090(14)
J/ψ	3.097	1.91	5.53	6.34×10^{-3}	3.89×10^{-3}	$6.4(1.1) \times 10^{-3}$
Υ	9.46	5.16	1.34	0.196×10^{-3}	0.062×10^{-3}	$1.7(0.1) \times 10^{-3}$

Summary

- We developed the P-dyn reaction model for vector-meson photoproduction, $\gamma + p \to V + p$. It describes the photon-to-meson transition through a dressed quark loop and connects it to the proton's valence quarks via Pomeron exchange.



- P-dyn successfully describes measured differential and total cross sections over a wide range of energies. The quark loop is essential. Non-diffractive processes become important near threshold, especially for ρ production near threshold.



- P-dyn predicts the high-energy power-law behavior of total cross sections, in good agreement with data. For light mesons, the exponents differ from simple Pomeron predictions.

- Near-threshold slope parameters were extracted using P-dyn. The slope for ρ production may be underestimated because of nondiffractive effects, while results for other vector mesons are more reliable.

- P-dyn provides a unified description of forward vector-meson photoproduction from threshold to high energies. Pomeron exchange is the model's only explicit link to gluon dynamics, but it has no established connection to the proton's gluon distributions.

- Near-threshold vector-meson photoproduction cannot yet reliably constrain proton gluon distributions. Better reaction models and more precise data are needed before a firm connection to proton structure can be established.

Thank you!

